COST COMPARISON OF HYDROPOWER OPTIONS FOR RURAL ELECTRIFICATION IN RWANDA

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&

Dr. R. Herman

September, 2012

DECLARATION

I declare that this postgraduate thesis "Cost comparison of hydropower options for rural electrification in Rwanda" is my own work. It has not been submitted to any other University for the same degree or examination. All sources that I have used or quoted have been indicated and acknowledged in the references.

Anicet NSENGIYUMVA Signed by candidate Date: 17 September 2012

Signature Removed

DEDICATION

This dissertation is dedicated to whoever who contributed in my studies.

May Almighty God bless you all!

ABSTRACT

The decision to develop a hydropower plant depends on several factors, which cost is the most significant. This thesis, entitled "Cost comparison of hydropower options for rural electrification in Rwanda" intends to show that the use of a large number of mini hydropower plants for electrification of sparse rural areas in Rwanda is the least cost option when compared to installing either a single small or large hydropower plants.

This is done by considering rural households to be randomly distributed and the model composed by 98 rural villages having three different population densities is used to test the validity of the hypothesis.

Three different hydropower options providing the same level of service to rural households were used for the cost comparison. The relationship between the electrification cost per household versus the population density is deduced.

Many distribution technologies can be used in rural areas and the accurate selection of the appropriate distribution technology is the main concern as it affects the cost of the whole distribution system. The rural network should be carefully designed so that the sizing of conductors to be used for LV and MV network is properly done at a low cost.

The high distribution cost depends largely on the size of power to be delivered. Based on these findings, the cost comparison of mini, small and large hydropower schemes for rural electrification in Rwanda is discussed.

ACKNOWLEDGEMENTS

First of all, thanks are to God for helping me in making this thesis possible.

Amongst a wide panorama of people who provided me help and motivation, my sincere thanks are expressed to Prof. Gaunt C.T and Dr. R. Herman for their supervision, guidance and encouragement throughout this research. You have been the source of motivation and help during my Master's degree program.

My special thanks are also expressed to my Wife Janviere UWIMANA for her motivation and support during this work. Even if you were so far away, your support has been of great importance and your love gave me the confidence and the drive to realize my dreams.

Thanks go also to all Power Engineering Group members and fellow students at UCT. Your usual collaboration has served a lot and you will always be in my heart.

Last but not certainly least; I would like to thank the Government of Rwanda for having agreed to sponsor my studies.

May Almighty God bless you all!

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LIST OF ABREVIATIONS

AAAC	All Aluminium Alloy Conductor
ABC	Aluminium Bundled Conductor
ACSR	Aluminium Conductor Steel Reinforced
ADMD	After Diversity Maximum Demand
CEPGL	Communauté Economique des Pays des Grands Lacs
COMESA	Common Market for Eastern and Southern Africa
ESMAP	Energy Sector Management Assistance Programme
EWSA	Energy, Water and Sanitation Authority
GDP	Gross Domestic Product
GNESD	Global Network on Energy for Sustainable Development
Ha	Hectare
HH	Household
HV	high Voltage
IEA	International Energy Agency
km	Kilometre
kV	kiloVolt
kW	kilowatts
LV	Low Voltage
m	Metre
MININFRA	Ministry of Infrastructure
MV	Medium Voltage
MW	Megawatts
NISR	National Institute of Statistics of Rwanda
Pdf	Probability density function

RECO-RWASCO Rwanda Electricity Corporation-Rwanda Water and Sanitation Corporation

SINELAC Societe Internationale d'Electricite des pays des Grands Lacs

SNEL Societe Nationale d'Electricite

SWER Single Wire Earth Return

TWh TelaWatt hour

UNIDO United Nations Industrial Development Organization

USD United States Dollar

V Volts

1 INTRODUCTION

1.1 General introduction

The lack of electrification infrastructures in rural areas of most African countries is still a barrier to social and economic development. One of the causes is the dispersion of the population and the long distances of rural villages to the existing electricity network infrastructures. Another strong reason is the financial situation of the governments which doesn't allow them to invest sufficiently in electrification of rural areas.

The adoption of European standards for electricity distribution networks by many African countries is another issue that should be mentioned. These standards were developed for high density and high demand centres in Europe and when applied in low density areas, they result in oversized networks with unnecessarily high costs for connecting small rural loads [ESMAP, 2006].

For a country like Rwanda, where the access to electricity is less than 10% countrywide and less than 2% in rural areas, access to electricity in rural areas becomes a subject of discussion when almost all the hydropower resources are located nearby the rural villages but the electrification rate is still very low.

For these reasons, the aim of this project is to compare the cost of electrification of rural villages using hydropower schemes of different sizes; from small and mini hydro schemes. This analysis is aimed at improving decision making in developing countries where potential exists for hydropower development and rural electrification is needed.

1.2 Description of Rwanda

Rwanda is a small mountainous landlocked country located in Central Africa, bordered to its south by Burundi (for about 290km), Tanzania to its east (~220 km), and Uganda to its north (~170km) and the Democratic Republic of Congo (DRC, formerly Zaire) to its west (217 km). Rwanda has a total surface area of 26, 338 km² of which the total land is ~95% and water is ~5% (24,948 km² and 1, 390 km²) [MINITERRE, 2003].

From the economic point of view, Rwanda is one of the poorest countries in the world. Its economy is basically agricultural. More than 90% of the population depend on peasant subsistence agriculture which contributes 40% of GDP estimated at 210 US$ in 2000 and

90% of export earnings. The industrial sector is still in its early stages. The secondary sector of the economy employs 2% of the working population, 0.2% of who are women. The services sector employs not more than 6.6% of the population, 4.1% of whom are men and 2.5% women. The informal sector represents 79.80% of employment and the public and semi-public sector represents only 2.4% in the town of Kigali.

1.2.1 Relief

Rwanda is often referred to as the country of a “thousand hills” because of its numerous highly dissected hills, often with flat peaks and convex slopes, separated by relatively narrow valleys, with the lowest altitude of 950m at Rusizi River and the highest altitude at Mount Karisimbi 4,519 m. The average altitude is 1,250 m above sea level.

1.2.2 Climate

Rwanda enjoys a tropical temperate climate due to its high altitude. The average annual temperature is 16°to 20°C, without significant variations. Rainfall is abundant although it has some irregularities (similar at the Congo-Nile ridge; much lower temperatures, partially below 0°C, in the volcanic region). Winds are generally around 1-3 m/s.
In areas with intermediary altitude, average temperatures vary between 19 and 21°C and the average rainfall is around 1000 mm /year. Rainfall is less irregular, and sometimes causes periods of drought. In the lowlands (east and southeast), temperatures are higher and with maximum up to 32°C in February and July-August, and rainfall being less abundant here (700 to 970 mm/year).

Weather in Rwanda is determined by the rainfall patterns. Thus, the climate of the country is characterized by an alternation of four seasons of which two are wet and the other two are dry. However, rainfall is generally well distributed throughout the year, despite some irregularities. Eastern and South-Eastern regions (Umutara, Kibungo, Bugesera, and Mayaga) are more affected by prolonged droughts while the northern and western regions (Ruhengeri, Gisenyi, Gikongoro and Byumba) experience abundant rainfall that usually causes erosion, flooding, and landslides.
The quantity of total annual rainfall varies between 800 mm in the Northeast of Rwanda (Eastern Umutara) and 1600 mm in the natural forest of Nyungwe (Wisumo) and in the high lands of the Northwest (Kinigi). The region that is characterized by the highest rainfalls

(over the average isohyets of 1200 mm) is located in the western half of the country including the region bordering Lake Kivu.

1.2.3 Catchments and hydrology

Rwanda has a relatively big quantity of water: rivers, lakes and marshes and occupy a surface area of 211000 ha or about 8% of the national territory (lakes: 128000 ha, rivers: 7260 ha and marshes: 77000 ha).
Rwanda is divided into two major drainage basins, the Nile to the east and the Congo to the west. The Congo River Basin covers 25 percent of Rwanda and receives 10 percent of the total national rainfall. The rainfall regime has a strong influence on the hydrological regime. The country experiences floods during the long rainy season (March – May) and floods subside during the long dry season (June – September). Low water levels are very marked.

The Congo basin consists only of insignificant and short rivers, which flow into Lake Kivu. River Rusizi in the south is its outflow towards Lake Tanganyika. The Nile basin covers the greatest part of the territory. Most rivers originate from the slopes of the Congo-Nile ridge. The two main rivers, namely Nyabarongo and Akanyaru, together with their numerous tributaries form downstream from Lake Rweru, the river Akagera which drains the best part of Rwanda's waters towards the Nile, forming the border with Burundi in the south and Tanzania in the east. Rivers Nyabarongo and Akagera are closely associated with vast marshes and numerous shallow lakes found along these rivers. The ecology of these ecosystems is very dynamic and complex; the vegetation of marshes and the size of the lakes change continuously with the rainfall and the flow rate of the rivers.

1.2.3.1 Lakes

Rwanda has some 28 lakes of significant size. Three, Rweru, Cyohoha and Kivu, are shared with neighbouring countries with Lake Kivu being by far the largest: (1,460m above sea level; 90 km long (N-S) and 49 km wide (E-W); average/ maximum depth 220m/475m. Lake Kivu's shores are densely populated. Although there are some fishes, the lake is poor in fauna but rich in volcanic substance. Great volumes of dissolved methane gases exist in its deep waters. Lake Kivu drains to the south into Lake Tanganyika by the swiftly descending Ruzizi River. The Central Plains are drained by the Nyabugogo, and Akanyaru rivers.

Rwanda's eastern border is formed by the Akagera River on its way to Lake Victoria. The rivers and lakes cover some 135,000 ha, or 5% of national territory.

1.2.4 Population

Rwanda is characterized by the average population density of 328 inhabitants/km^2 [NISR, 2007]. The population of Rwanda was estimated to 10 million inhabitants in 2008, sharing a territory of 26,338 km^2. Most of Rwandans live in rural areas and mainly in isolated houses. The overall population is high but the rural areas of the country are characterized by low population densities. Figure 1-1 shows the population density distribution countrywide

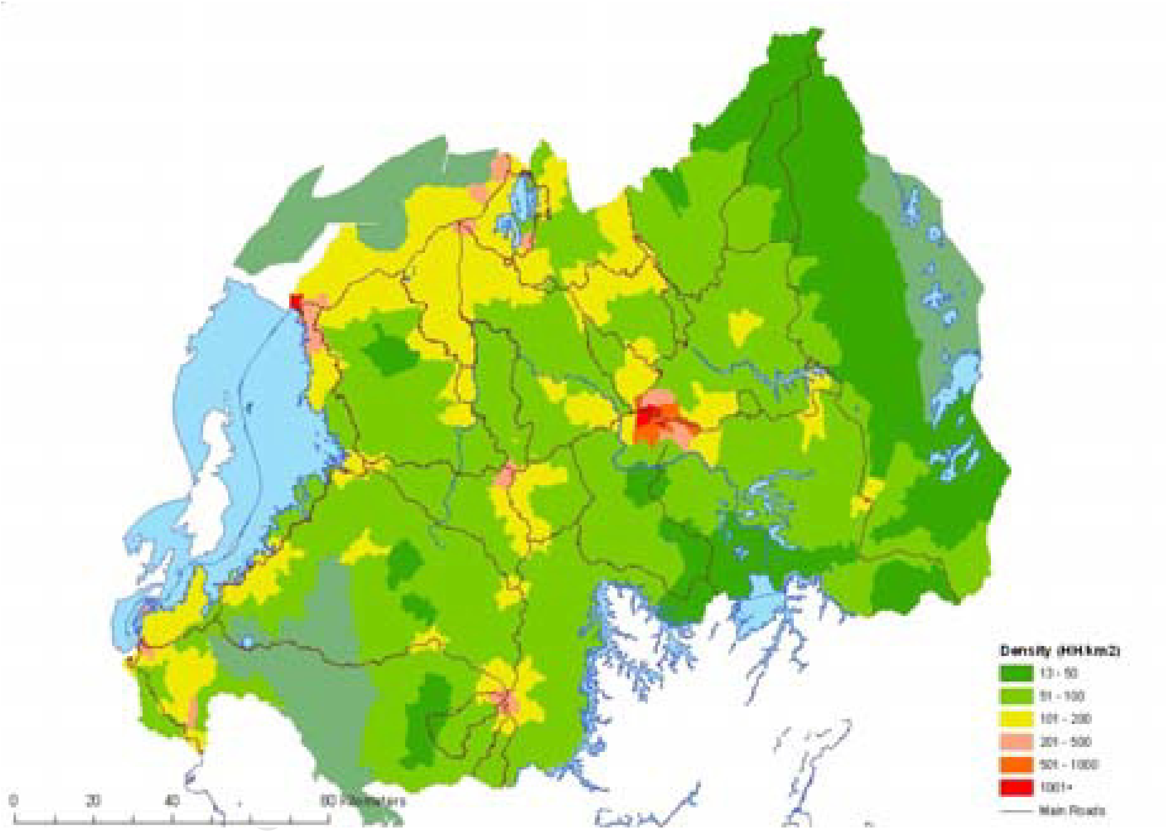


Figure 1-1: Population densities in different parts of Rwanda

Source: National Institute of Statistics of Rwanda, 2008

1.2.5 Economic and political situation of Rwanda

Rwanda is classified among the World wide country with low economy growth because its economy has been completely destroyed during the war of 1994.

Although handcraft is the common characteristic of the economy sector of Rwanda, it has a very important place after agriculture; it is considered as the second employer of the country along with painting, carpentry, silversmith's trade and art handcraft.

Rwanda's economy is still depending on the international donors. Thus the Government of Rwanda (GoR) is increasing the cooperation with the countries in the region; it is currently a member of the East- African community. Rwanda is also a member of Great Lakes Economic community (CEPGL), member of Common Market for East and Southern African countries (COMESA).

The Government of Rwanda is committed to boost the economy by focusing on the development of the basic infrastructures like road and electricity. The increase in exports of coffee and tea, and applying the policy of privatization and liberalization is another approach to boost the economy.

Moreover, the government is promoting strongly the education and healthcare sector to ensure the long-term quality of Rwanda's human resource skills base.

Few figures characteristic of the population of Rwanda are summarized in table 1-1.

Table 1-1: Key figures characteristics of Rwanda

Source [NISR, 2007]

Parameter	Value
Area	26,338 km^2
Population	8,128,5535, around 10.2 million in 2006
Population density	328 per km²
GDP per inhabitant	272 US $
Capital city	Kigali (estimated population 800,000)
Official languages	English, French and Kinyarwanda
Urban population	8% of the total population (2006 estimates)
Life expectancy	41 years (2006 estimates)
GNP	US$1.817 billion (est. 2006)
Real GDP growth	5.8% (2006 estimation)
Agriculture	39.4% of the GDP
Industry	23.23% of the GDP

Services	37.3 % of the GDP
Religion	Christian 93.5% and 4.6 % Muslim
Main exports	Coffee, tea, cassiterite, coltan and small gold
Main imports	Production good, capital in kind, food
Currency	1US$ = 557 RWF
Weather	Tropical highland climate. Two rainy seasons: March-May and October-December Average temperature 24°C (maximum 34°C in day and 10°C at night - 19°C in Kigali)

1.3 Overview of electrification in Sub-Saharan Africa

Today's world is looking for an efficient way for electricity supply so as to influence development and improve the livelihood of the people. An International Energy Agency report [IEA, 2002] has shown that more than 1.6 billion people around the world lack access to electricity.

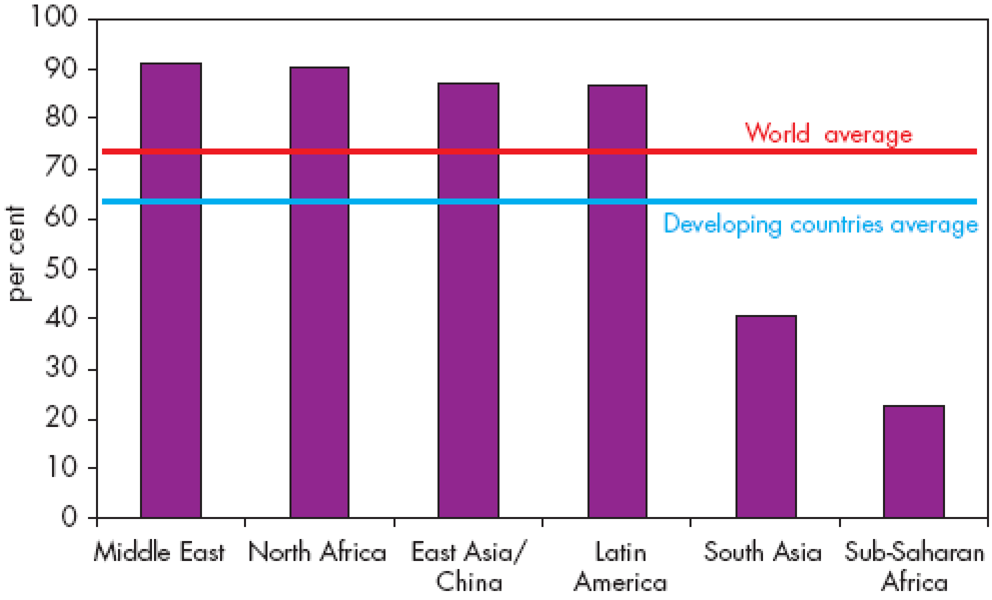


Figure 1-2 Worldwide electricity access

Source: IEA, 2000

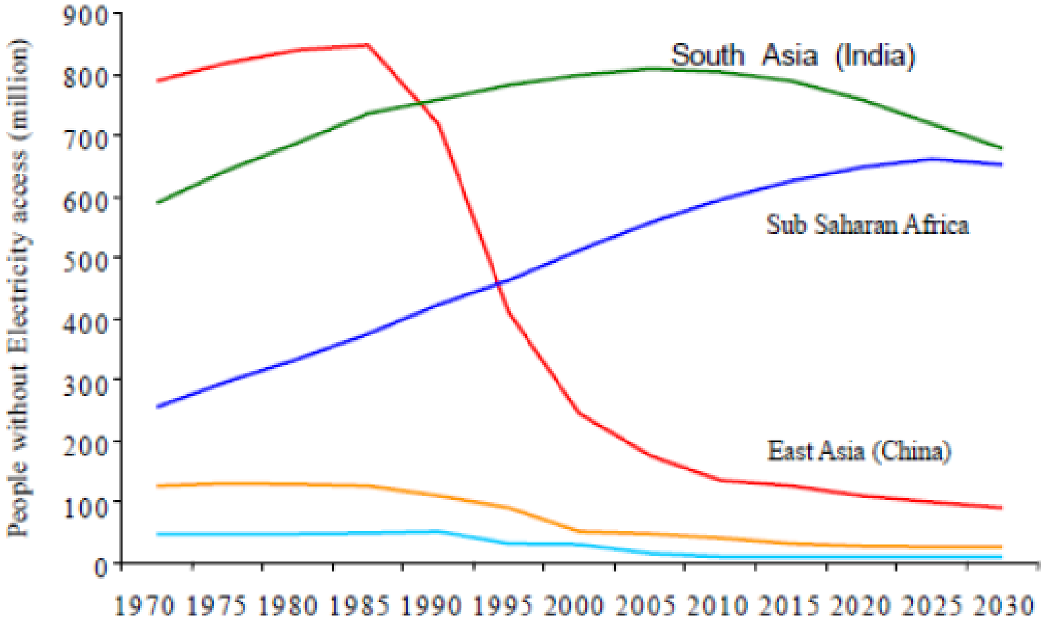


Figure 1-3: Regional Electricity access: A comparison

Source: IEA, 2002

According to figure 1.2, the sub-Saharan Africa is the least electrified with only 23% of the population with access to electricity. The predictions in Figure 1.3 show that there still a lot to do in order to reduce the number of people without access to electricity in Sub-Saharan Africa. By 2030, more than 500 millions Sub-Saharan Africa people will still be without access to electricity. IEA [2002] concludes that the region's poverty is one reason, but also its low population density in rural areas which raises the cost of extending networks. This high cost of the network extension is mainly found in rural areas where the population live far from the existing grid. According to Global Network on Energy for Sustainable Development report [GNESD, 2007a] the inadequate supplies of affordable energy inhibits the improvement in health, education and poverty alleviation. Therefore, the lack of access to electricity is one of the poverty indicators.

1.4 Objectives

With the increase in the development of renewable energy sources worldwide and the aim of the government of Rwanda to supply electricity in remote areas, this research project on cost comparison of hydropower options for rural electrification in Rwanda was proposed. The project provides the opportunity to investigate the applicability of a range of different hydropower approaches to meet electricity needs in rural areas of Rwanda. The objective of this project is to compare the costs of supplying electricity to rural households in remote areas of Rwanda where the population densities are low and there is availability of rivers that can be used for small and mini-hydropower plants construction.

1.5 Scope of the research

The study involves three cases:

Case 1: Mini-hydropower plants are used to supply electricity to a certain number of villages in close proximity. In this case, each mini-hydro scheme is used to supply specific villages using short MV distribution lines and MV/LV transformers.

Case 2: One small hydropower plant is used to supply electricity to many villages. In this case, long MV distribution lines are used to interconnect all the villages and MV/LV distribution transformers are used to supply electricity to various rural households.

Case 3: A medium hydropower plant (10MW) is used to supply electricity to many rural villages. In this case, long MV distribution lines are used to interconnect all the villages and MV/LV distribution transformers are used to supply electricity to various rural households.

The goal of the work adopted in this research is to analyze the problem of rural electrification in Rwanda by comparing the costs involved in different modes of hydroelectricity power supply (i.e. mini-hydro, small hydro and medium hydro). Furthermore, with the help of this research, policy makers will be able to decide in advance; which approach is financially viable for electrification of the rural areas due to the nature of its load density. A number of factors such as: the population density, the length of MV and LV distribution lines and the associated costs will be taken into account.

Therefore, this thesis aims at establishing the cost comparison for different rural distribution systems using mini and small hydropower plants in Rwanda.

1.6 Hypothesis and research questions

The hypothesis to be tested by the research was formulated as follows:

"Rural electrification in Rwanda could be carried out most appropriately using mini hydropower plants with short distribution lines instead of using small hydropower schemes with long distribution lines."

In order to test the validity of the above mentioned hypothesis, a set of the research questions has been adopted.

1) What is the status of electrification in Sub-Saharan Africa and what is the situation in Rwanda?

2) What are the different types of hydroelectric power plants and how can these be applied to rural electrification?

3) What are the different electricity distribution technologies and which one is cost effective as far as rural electrification is concerned?

4) How can the rural electrification model be done?

5) What is the impact of the population density on electricity distribution system infrastructures?

6) What is the approximate cost of supplying electricity to a typical rural household in Rwanda using mini, small and medium hydropower schemes?

7) Which hydropower option is the least cost for rural electrification in Rwanda?

1.7 Methodology

The adopted methodology will help provide answers to the research questions which is one way to test the validity of the above mentioned hypothesis. This methodology comprises the following parts:

Literature review

- Use of available information from published articles to investigate the aspects of rural electrification using hydropower schemes.

- Investigate the types of hydropower plants and deduce the scales used in rural electrification.

- Investigates different rural distribution technologies and identify the appropriate design of a reliable rural distribution system.

Theory development

This part of the research deals with the establishment of steps and procedures that will be followed during the analysis of this work. It establishes the relationship between the population density and the length of LV network required for households' interconnection.

Study case

This consists of using analysis methods to conduct a study on rural electrification in Rwanda.

In this case, the electrification of a sample of villages having different population densities will be done using two different hydro schemes and the distribution cost per household will be used for comparison of the two options.

Discussion of the results

This part contains the interpretation of the results obtained and shows the benefits that can be offered by either using mini-hydro or small hydropower plants for rural electrification in Rwanda.

Conclusion and recommendations

The last part of this work gives the general conclusion about the development of mini and small hydropower schemes for rural electrification in Rwanda. The advantages and disadvantages of each alternative are compared and the decision to adopt one of the options is based on the least cost option and the population density.

1.8 Relevance of Research

This research will help policy makers and people involved in rural electrification projects to know the impact of the dispersed population density on the cost of a rural electrification project. Specifically to Rwanda, this research will help in decision making for rural electrification projects in regions where hydropower resources are available. It is hoped that the outcomes of this research will also help in proper design of cost effective rural electricity networks.

1.9 Outline of Dissertation

The structure of the thesis is as follows:

Chapter 1: General introduction which gives a general overview of the research; sets the hypothesis to be followed and the research questions used to test the validity of the hypothesis.

Chapter 2: The literature review is about the background knowledge on the topic. In this part, hydropower plant technologies are discussed from the published articles. Electrification overview in Rwanda is discussed and the role of hydroelectricity in Rwanda is shown. This chapter also discusses different rural electrification technologies and helps in selecting the cost effective technology to be used.

Chapter 3: Development of the framework for the analysis. Here, investigation on how the population density affects the length of LV network will be discussed and the relationship between the population density and the LV network length is established. This part serves as the basis to determine the cost involved in electrification of different types of villages.

Chapter 4: Application of the approach developed in Chapter 3 to design the rural electrification network using mini and small hydropower schemes.

Chapter 5: Cost of a rural electrification of 98 villages in Rwanda using a large number of mini hydropower plants.

Chapter 6: Cost of a rural electrification of 98 villages in Rwanda using a single small hydropower plant.

Chapter 7: Discussion of the results obtained in Chapter 5 and 6.

Chapter 8: Conclusion and use of the outcomes from the overall research results to prove the validity of the hypothesis and give the recommendations.

2 LITERATURE REVIEW

2.1 Introduction

This chapter is intended to review the literature that is related to the objectives of this thesis. This chapter discusses electrification in Rwanda, hydroelectric power technology and its cost and the use of Mini and small hydro for electrification in Rwanda. The information collected in this part will serve as the basis of a rural electrification project planning. The cost comparison of rural electrification in Rwanda using mini and small hydropower plants will be deduced later.

2.2 Electrification in Rwanda

To understand the context in which electrification activities are taking place in Rwanda, it is important to consider the country's existing grid, electricity generation projects and the effect of the dispersed population on electrification projects.

2.2.1 Rwanda's grid development and electricity generation

As reported by Rwanda Electricity Corporation (RECO), electrification level in Rwanda is very low with only 10% of the population having access to electricity. In rural areas this percentage falls to less than 2% [RECO-RWASCO, 2009]. By the end of 2008, RECO-RWASCO (Former Electrogaz) had over 100,000 customers, of which approximately 60% are in the capital city (Kigali). This explains again the low level of electrification in rural areas of Rwanda. The scattered population makes electrification by grid extension to be very costly. According to [RECO-RWASCO, 2009], around 75% of the country's population lives in small and scattered rural settlements. Figure 2-1 shows the geographical coverage of the electricity network in Rwanda and the location of generation.

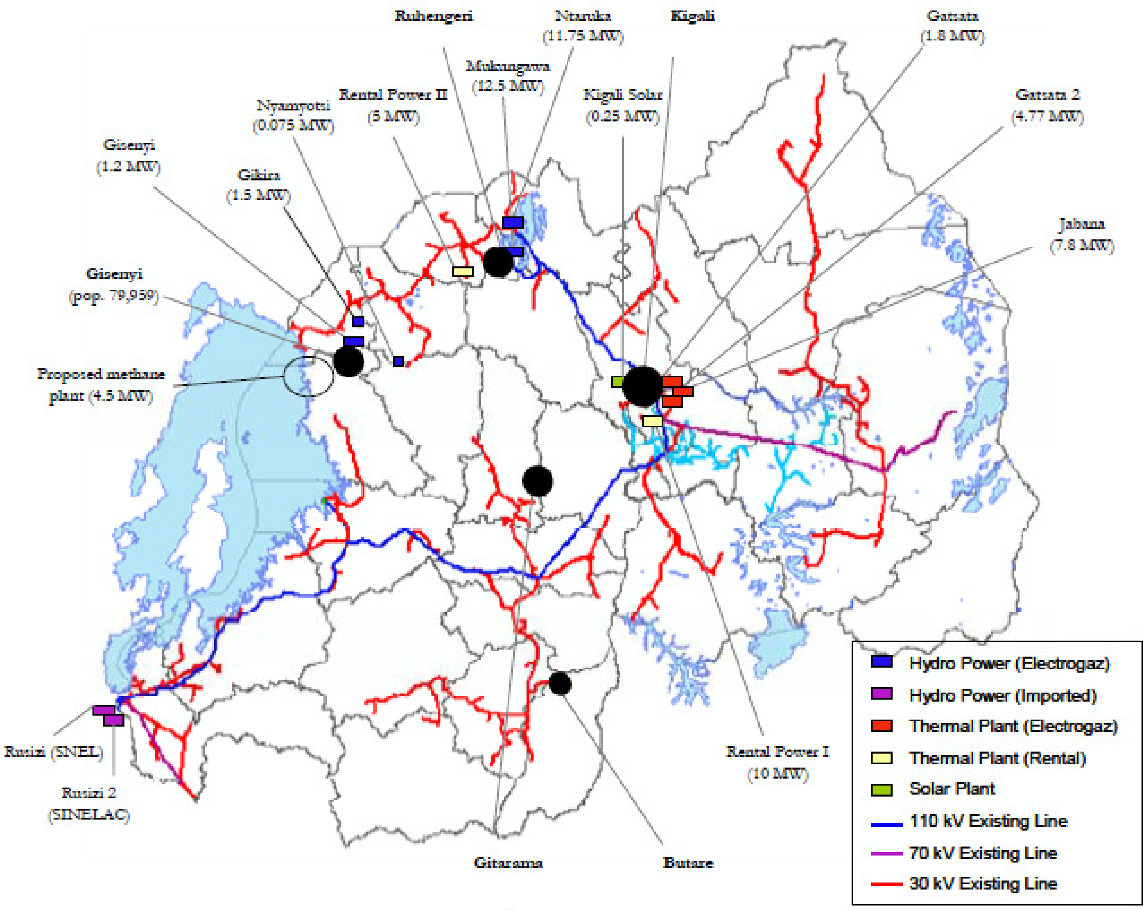


Figure 2-1: Geographical coverage of electrical network in Rwanda and location of generation

Source: Mininfra, 2009

The national transmission grid, which is illustrated in Figure 2-1, consists of some 285 km of 110 kV lines and 64 km of 70 kV lines. The distribution system consists of both medium voltage (30 kV, 15 kV and 6.6 kV which is being upgraded to 15kV) and low-voltage (380 V three-phase and 220 V single-phase) networks, with a significant proportion being located in Kigali.

As shown in figure 2-1, electricity generation in Rwanda is dominated by hydro. This is explained by the recent Hydropower Atlas project that has identified 333 hydro sites in the country with a combined capacity of 96 MW. Rwanda's share of hydropower potential on border rivers is at least 115 MW [Mininfra, 2009]. Table 2-1 shows the electricity generation capacity as at January, 2009.

Table 2-1: Electricity generation in Rwanda: Capacity as per January, 2009

Source: Mininfra, 2009

Category	**Name**	**Installed capacity [MW]**
In house hydro Power	Ntaruka	11.75
	Mukungwa	12.5
	Gihira	1.8
	Gisenyi	1.2
Imported hydro Power	Rusizi 1 (SNEL)	3.5
	Rusizi 2 (SINELAC)	12
Micro hydro Power	Nyamyotsi	0.075
In house Thermal Power	Jabana	7.8
	Gatsata 2	4.77
	Gatsata 1	1.8
Rental thermal Power	Aggreko 1 (Gikondo)	10
	Aggreko 2 (Mukungwa)	5
Solar Power	Kigali solar	0.25
Total		**72.4**

2.2.2 Dispersed population

At present, 75% of Rwanda's population lives outside the cities in small scattered rural settlements. This dispersed nature of the population makes electrification by grid extension very costly especially if the three phases Low Voltage Distribution is used. The Government initiated a strategy to move rural households into grouped settlement for easy access to electricity in rural areas.

2.2.3 Need of off-grid solutions for rural electrification

According to [RECO-RWASCO, 2009], the need of off-grid solutions for electrification of rural areas in Rwanda was strengthened by the experience gained by the countries such as Sri-Lanka, Nepal, Indonesia and Vietnam. The common finding is that for any location with a distance closer than 4km to an existing MV line, a grid connection is more economic for consumer than the cheapest off-grid solution which is Pico or Mini hydropower assumed to be near the consumer. In case of rural areas in Rwanda, they are isolated and far from the existing MV lines. For this reason and since most of them are in close proximity of rivers, they can be electrified using Mini and Small hydropower plants.

2.3 Hydropower plants

The history of hydropower dates a long time ago. According to [Canadian Hydropower Association, 2011], people have been using water potential energy for more than two thousand years starting with the wooden water wheels that were used to grind wheat into flour as early as 100 before Christ in many parts of Asia. According to Fraenkel et al., 1991; the 19th century brought improved engineering skills and the need for electricity generation caused the turbines to replace the water wheel.

Hydropower is energy from water sources such as rivers, waterfalls and oceans. The basic principle of hydropower systems is that if water can be piped from a certain level to a lower level, then the resulting water pressure can be used to perform work. If this water pressure is used to move a mechanical component, then the movement involves the conversion of water energy into mechanical energy [Fraenkel et al., 1991]. Hydro turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator, a grain mill or some other useful device [Fraenkel et al., 1991, Mewang, 2006].

Hydropower is generated from flowing water by extracting the energy of water movement by electricity generators. The origin of hydropower was in milling practices or agricultural use, but today many of the rivers are used to produce electricity through hydro generators [Boyle, 2004, Alternative Energy, 2009].

2.3.1 Hydropower energy in the world

As a source of renewable energy, hydropower has a big role in electrical energy production worldwide. According to [Paish, 2002], the world's technically feasible hydro potential was estimated to 14,379TWh/year. The potential that can be economically exploited is 8,080TWh/year and the exploited potential in the world in 1999 was 2,650 TWh which was equivalent to 19% of the world's electricity. In 2001, Canada was the world's biggest producer of hydropower generating 350TWh/year which is 13% of the global output.

Figure 2-2 shows the annual energy generated by hydropower plants and economic potential for some countries [ERE, 2005].

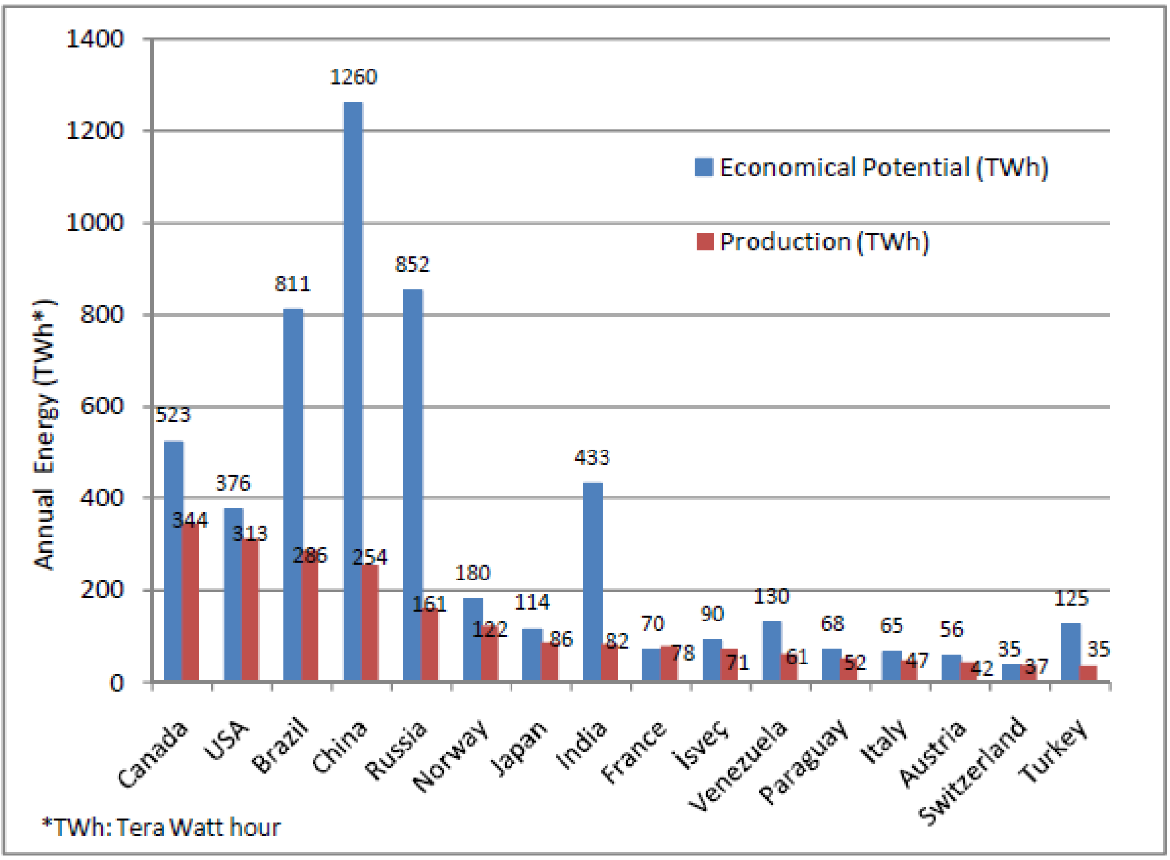


Figure 2-2: Hydropower annual energy generation and economic potential for some countries

Source: ERE, 2005

2.3.2 Advantages and disadvantages of hydropower plants

The following are the advantages of hydropower plants [Kormaz, 2007]:

- The use of the power of flowing water without wasting made hydropower to be accepted as a renewable source of energy.
- Hydropower plants with reservoir provide operational flexibility that allows them to respond to changes in electricity demands.
- Hydropower reservoirs can be used for water supply in irrigation and they help to reduce the effects of floods.
- Hydropower is a clean source of electricity because it does not generate toxic waste products, air pollution reduction and slow down the global warming.

- Hydropower facilities bring electricity, roads, industry, commerce and employment to rural areas, developing the regional economy, and increasing the quality of life.

- According to [Kesharwani, 2006], Hydropower projects that are developed and operated in an economically viable, environmentally positive and socially responsible manner represent sustainable development.
- Hydropower provides national energy security which is a key issue for developing countries. Water used from rivers is a natural resource that is not subject to fluctuations in fuel prices.
- Hydropower is an affordable power supply option due to its very low operating and maintenance costs and its lifetime that extends up to 50 years.

The disadvantages of hydropower plants include [Kormaz, 2007]:

- The environmental impacts of dam construction including the problems related to relocation of people.
- Dams containing huge amounts of water have the risk of failure which may cause catastrophic results such as flooding.
- The initial cost of construction is high because of the dam construction and site facilities.
- Hydropower can only be used in areas where there is sufficient water flow.

2.3.3 Working principle of hydropower plants

The conversion of water pressure into mechanical shaft power by turbines which can be used to generate electricity by generators is the basic principle of hydropower plants. The hydroelectric power capacity of a hydroelectric power plant is directly proportional to the gross head and discharge. The following formula can be used to determine the power generated by a hydroelectric power plant [Kormaz, 2007]:

$$P = e\rho g Q h_g \qquad (2.1)$$

Where:

P: Power in Watts

e: Overall efficiency of the system

ρ : is the density of water (1,000kg/m^3)

g: Acceleration due to gravity (9.81 m/S^2)

Q: Water discharge passing through the turbine (m^3/S)

h_g : Total head (m)

The following is the working principle of a typical hydroelectric power plant [Kormaz, 2007]:

- Water from the reservoir or the river flows through the canal and then passes to a penstock.
- This flowing water pushes the turbine's blades and makes the shaft to rotate.
- The rotation speed of the shaft is the same as the turbine's speed and the shaft is connected to the generator.
- The spinning shaft turns magnets inside a stationary ring of copper, moving electrons to produce electricity.
- Step-up transformers increase the voltage of electricity produced by the generator.

Figure 2-3 shows the main components of a hydroelectric power plant.

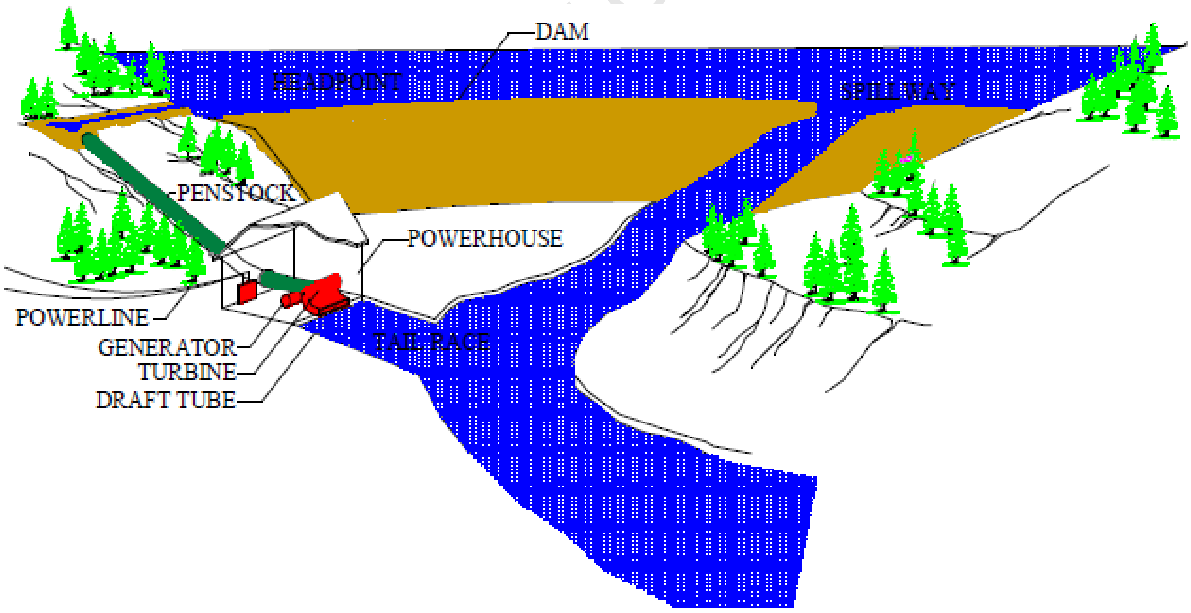


Figure 2-3: Components of a hydroelectric power plant

Source: Kormaz, 2007

2.3.4 Classification of hydropower plants

According to Williams and Porter, 2006; hydropower schemes vary from large to very small. The biggest schemes involve damming huge rivers and supply large urban population centres with electricity. The construction of a dam across the river creates a storage reservoir and an increase in hydrostatic head. A powerhouse in which generators and turbines are installed is built at the bottom of the reservoir. The storage capacity of the dam helps to reduce the effects of seasonal changes in river flows and allows regulation of releases through the turbines.

According to [Williams and Porter, 2006], these large hydro-schemes are usually grid connected, but smaller projects may serve localized users, particularly in rural areas. Run-of-river systems don't rely on a reservoir and the generating capacity can vary depending on seasonal flows. Run-of-river schemes can vary in size significantly but many are relatively small and often not grid connected. Mini and Pico systems typically use the high heads and small flows and their small generating capacity makes them suitable for isolated off-grid locations to provide power to small rural communities.

There is no standard classification of hydropower plants as this varies from one region to another. According to [RETScreen, 2004-a], small hydro power plant capacities typically range in size from 5 MW to 50 MW. Projects in 100 kW to 5 MW range are sometimes referred to as small hydro and projects less than 100 kW are referred to as mini hydro. However, installed capacity is not enough to define the size of the project.

Table 2-2 below shows the classification according to the European Union.

Table 2-2: Hydropower classification by generating capacity

Source: Williams and Porter, 2006

Classification	Power output
Large	> 100MW
Medium	10-100MW
Small	1-10MW
Mini	100kW-1MW
Micro	5-100kW
Pico	< 5kW

According to [UNIDO, 2010], the classification is slightly different as shown in table 2-3.

Table 2-3: Hydropower plants classification and their use

Type	Power output	Use
Conventional hydropower	>10MW	Electricity supply, Feeding into the grid
Small hydropower	1-10MW	Electricity supply, Feeding into the grid
Mini hydropower	50-2000kW	Isolated, decentralized electricity supply, Feeding into the grid
Micro hydropower	<50kW	Direct drive of machines, electricity supply for isolated grids, seldom connection to national grid

Source: UNIDO, 2010

As shown in this section, the classification of hydropower is mainly dependent on the capacity of the plant. For the purpose of this study, the classification as shown by the European Union as illustrated in table 2-3; will be adopted and the terms mini and small hydropower schemes will be used.

2.3.5 Small hydropower and rural electrification

Electrification is considered to be one of the keys to development as it provides light and power used in production and communication. According to the World Bank report, the world's poor spend more than 12% of their income on energy and around 1.7 billion people do not have access to electricity [Laguna et al., 2006]. This reason necessitates the development of mini and small hydroelectric power plants as renewable energy sources suitable for rural electrification in poor and developing countries. Despite this fact, in 2004, the contribution of small hydropower having a capacity below 10MW contributed about 2% of the total worldwide electricity generation capacity.

Table 2-4: Worldwide small hydropower (<10MW) installed capacity in 2004

Source: Laguna et al., 2006

Region	Capacity [MW]	Percentage
Asia	32,641	68%
Europe	10,723	22.3%
North America	2,929	6.1%
South America	1,280	2.7%
Africa	228	0.5%
Australia	198	0.4%
Total	47,997	100%

According to the above shown hydropower capacities, Asia comes first in small hydropower development. According to [Laguna et al., 2006], China represents more than a half of the world's small hydropower installed capacity in 2005 with 31,200 MW.

The use of hydropower plants for rural electrification has increased worldwide as this is the most mature technology of the modern small-scale decentralised energy supply technologies used in developing countries [Khennas et al., 2000]. A large number of mini-hydropower plants operate successfully in China and other countries such as Nepal, Sri Lanka, Pakistan, Vietnam and Peru. This experience shows that there is a strong positive interest in investing in small and mini-hydropower plants for electrification of rural remote areas [Khennas et al., 2000].

2.4 Cost of a hydropower plant

According to [Vaidya, 2005], the construction cost of a hydropower plant may be site specific and varies depending on the site location and its physical components such as, civil works, generating equipments (turbine, generator, control, protection) and grid access costs. electrical distribution lines. While the cost of generating equipment in the power house is almost proportional to the kW size of the plant, the cost of civil works depends on the site layout. In the same manner, the cost of transmission lines depends on energy density of the load centres. This causes the unit cost of a hydropower plant installation to vary from scheme to scheme and to be site specific. The literature review indicates the various costs per kW generated by hydropower plants. According to technology brief ET12 of the Energy Technology Systems Analysis Programme [May, 2010], $4,000, $4,500 and $5,000 were taken as the average costs per kW produced by large, small and very small hydropower plants. On the other hand, the experience in construction of mini-hydropower plants in Sri-Lanka, Peru, Mozambique and Zimbabwe; shows the averages of $3,000 and $2,500 per kW for mini and small hydropower plants construction [Khennas et al., 2000]. These low costs per kW generated by a hydroelectric power plant can be achieved if low cost equipments are used as is the case in Sri-Lanka where most of the equipments are locally manufactured.

2.5 Hydropower in Rwanda

Hydropower in Rwanda plays an important role in electricity generation. This is due to the topography of the country; having abundant rivers and flowing water sources. As shown in table 2-1, hydropower has a primary role in the sources of electricity generation in Rwanda because of its percentage in power production countrywide. Different sources of electricity in Rwanda were shown in table 2-1 and table 2-5 shows specifically the recently completed and scheduled hydropower plants.

Table 2-5: Recently completed and scheduled hydropower plants

Plant	**Installed capacity [MW]**	**Available energy [GWh]**	**Available**
Rukarara	9	45	2010
Mukungwa 2	3.7	20	2011
Nyabarongo	28	165	2014
Rusizi 3	47	219	2014
Akanyaru	3.9	31	2015
Rusumo falls	20	148	2015
Rusizi 4 (Sisi 5)	83	430	2020
RC2	16	78	2025
Panzi	14	65	2025
Total	223.9	1201	

Source: RECO-RWASCO, 2009

From tables 2-1 and 2-5, it is obvious that hydropower plants play the main role in electricity generation in Rwanda. This is the reason for their consideration in electricity access programme.

2.5.1 Mini and small hydropower for rural electrification in Rwanda

Electrification of rural areas of Rwanda is normally by grid extension. Rural areas of Rwanda were found to be easily electrified by mini and small hydropower plants due to availability of water resources in these areas. As reported by Rwanda Electricity Sector Access Programme report [2009], a number of mini and small hydropower projects will be developed until 2013.

Table 2-6: Mini-hydro sites identified for potential development until 2013

Source: Mininfra, 2009

Potential [kW]	**Province**	**District**
500	South	Nyamagabe
750	North	Gakenke
500	South	Nyaruguru
100	West	Nyamasheke
25	South	Muhanga
50	West	Nyamasheke
25	South	Nyaruguru
25	North	Gakenke
50	West	Nyamasheke
25	South	Muhanga
50	West	Nyamasheke
25	North	Gicumbi
25	West	Nyamasheke
25	South	Nyamagabe
100	South	Nyaruguru
100	West	Karongi
25	South	Nyamagabe
50	West	Ngororero
250	South	Nyaruguru
100	West	Karongi
100	West	Ngororero
50	South	Nyaruguru
250	South	Nyaruguru
750	West	Rutsiro
50	South	Nyaruguru

These are few of the sites selected from hydropower atlas of Rwanda. They are micro and mini hydropower sites to be developed under the access programme until 2013. The total capacity expected from this development is 4MW.

2.5.2 Cost of a hydropower plant in Rwanda

As discusses in section 2.4, it is difficult to achieve the low cost to develop a hydropower plant in Rwanda due to landlocked structure of the country, the need to import most of electromechanical and hydro mechanical equipments and their transport costs. According to [MININFRA, 2011], the range of costs of hydropower plants currently under development in Rwanda is between 3,000$ and 4,500$ per kW generated by mini and small hydropower plants. These are the costs that will be applied in this study.

2.6 Rural distribution network

The reliability, cost and quality of an electrical network depends on the way it is designed. Network planning engineers are challenged and recommended to design and come up with a cost effective distribution network [Gaunt and Herman, 2005]. Even if networks for different configurations require different techniques, some aspects are almost the same. While network planning involves putting into consideration characteristics and parameters which affect the design of a network, designing means fulfilling the planning specifications. These are the two aspects of network design and planning [Brown and Gaunt, 2002]. According to [Stephen et al, 2001 (NSR 034)], a good distribution network design should minimize voltage drops, power losses and costs at the same time providing the highest level of reliability with voltage drop being the most important factor in sizing. Constant power, constant resistance and constant current are three different types of load models that exist, but the widely used is the constant current model [(Gaunt, 2003); (Gaunt and Herman, 2005); (Gaunt and Herman, 2008) (Gaunt, 1996)].

2.6.1 Factors affecting planning and design of distribution networks

There are a number of factors that are to be considered when planning and designing a distribution network. According to [Gaunt and Herman, 2005], some of these factors must be given special attention because they affect the demand of electricity by rural households. These are: Income, provision of piped water, circuit breaker limitation, and number of occupants, floor area, community habits, climate and distance from city centres. To ensure a better and a reliable design, the types of loads, their location and the magnitude of the targeted loads should be taken into account [Herman and Gaunt, 2008]. However, the designer may have some limitations to control all these factors [NRS 034-1, 2007].

Fixed parameters: These are parameters that cannot be changed by the designer.

- ✓ Residential structure
- ✓ Population density and geographical location
- ✓ Capital limitations

Limited or no control factors: These are factors that a designer cannot control or has a limited control.

- ✓ Variation of customers' load [Gaunt, 2003]
- ✓ Differing views of customers

Exercise control: These factors can be controlled by the designer

- ✓ Voltage limits and regulation
- ✓ Conductor size and type [Gaunt, 2003]
- ✓ Capital costs and life cycle costs
- ✓ Quality of supply
- ✓ The number and positions of metering points

2.6.2 Distribution network models

In order to achieve low cost connections, the factors mentioned in section 2.6.1 must be considered when choosing the technology to use. There are two different types of LV distribution networks used in developing countries. These are European and North American networks [Heunis et al, 2002]. The technologies that are used are:

- Three-phase four wire
- Three-phase three-wire
- Dual-phase
- Single phase

- Single Wire Earth Return (SWER) [Gaunt and Herman, 2005; Hossein-Zadeh and Wolfs, 2005]

These networks are characterized by MV/LV transformers with various rating such as 16kVA, 25kVA, 32kVA until 500kVA and a transformer can supply up to 300 households [Brown and Gaunt, 2002]. In addition to this, low density, long feeders and 50Hz are some of the other characteristics of rural distribution networks [Heunis et al, 2002]. In Rwanda, the distribution network uses 30kV and 15kV MV lines [RECO-RWASCO, 2009]. The use of SWER technology in Rwanda is recent and was introduced by the Tunisian company called STEG and is currently used for electrification of rural areas in the Eastern Province of Rwanda. This was done for cost reduction in rural electrification where three phase distribution lines are not necessary due to the nature of the loads to be supplied. These are relatively small loads and the use of single phase systems can satisfy the needs of electricity for rural households [RECO-RWASCO, 2009]. Aerial Bundled Conductor (ABC) is mainly used for LV feeders and the systems are normally 400/230V or 380/220V. Three phase four wire system is extensively used but SWER and single phase have also been used with MV transformers. According to [Carter-Brown and Gaunt, 2002], the model should be composed by the following:

- ✓ Load data: It consists of load factor, power factor, load size and distance from the source.
- ✓ Line data consisting of line capital cost, thermal ratings and impedances
- ✓ Financial data including but not limited to present value
- ✓ Generation cost: Energy and demand cost, covering the present value of fuel costs and spares.

According to [Hossein-Zadeh and Wolfs, 2005, Bellar et al, 2004 and Stephen et al, 2001; NSR 034-1, 2007], the following are the network configuration that can be used in rural electrification:

i. *Three-phase four-wire*

The distribution system has got three current carrying conductors and the fourth is a neutral wire which is grounded at several points [Hossein-Zadeh and Wolfs, 2005]. The loads are connected between one of the current carrying conductors and the neutral. Current harmonic effects in this configuration can be neutralized by a four wire active filter [Hossein-Zadeh and Wolfs, 2005, Bellar et al, 2004 and Stephen et al, 2001; NSR 034-1, 2007].

ii. *Three-phase three-wire*

This network configuration is widely used in Europe [Hossein-Zadeh and Wolfs, 2005]. It has three current conducting wires and there is no neutral connected to the ground.

iii. *Bi-phase*

The bi-phase system uses two current carrying conductors and a neutral which is connected to a centre taped single phase transformer [Gaunt, 2003, Hossein-Zadeh and Wolfs, 2005 and Stephen et al, 2001(NSR 034)]. This system is almost similar to three-phase three-wire configuration but the only difference is the neutral present in the dual phase system.

iv. Single Wire Earth Return

The network configuration uses one conductor with the return path through the earth [Hossein-Zadeh and Wolfs, 2005]. One side of the secondary transformer is grounded and the other side is used to supply electricity to the loads. The distribution transformers have their primary sides connected between the SWER line and the ground while the secondary side provides two low voltage phases with the neutral connected to the ground. Depending on the nature of the load, typical voltage of 19kV and 12,7kV are used [Hossein-Zadeh and Wolfs, 2005]. SWER lines normally get their supply from three phase distribution lines.

Table 2-7 shows some of the advantages and disadvantages encountered by each of the above mentioned technologies.

Table 2-7: Advantages and disadvantages of different rural electrification technologies

Technology	Advantages	Disadvantages
Three-phase four-wire	- Can sustain and supply heavy loads - Suitable for very long distances	- Difficult to design and construct - It is expensive, in terms of conductors, poles and transformers - Very expensive to maintain
Three-phase three-wire	The same as three-phase four-wire but cheaper due to absence of the neutral conductor.	Same as three-phase four-wire
Bi-phase	Same as three-phase three-wire.	Almost the same as above

SWER	- Easy to design and construct - Low cost due to one conductor and few poles - Easy and cheap to maintain - No line to line faults since there is no conductor clashing	- Line voltage rises due to the capacitive ground current during off-peak times [Martino et al, 2007] - The system capacity is limited by voltage drops [Bellar et al, 2004] - Low fault levels which makes it difficult to differentiate between peak loads and short circuit faults - Telephone interference [Gaunt, 2003; Hossein-Zadeh and Wolfs, 2005] - Limited load density - SWER systems are unbalanced loads on a three phase network - Difficult to control voltage [Hossein-Zadeh and Wolfs, 2005]

2.6.3 Distribution network cost reduction

The minimization of the distribution network cost can be achieved by careful consideration of its electrical characteristics. According to [Gaunt, 2003], the cost assessment of each network configuration must be done in order to design a cost effective distribution system. The following aspects must be evaluated:

- ✓ Cost of conductors
- ✓ Cost of structures
- ✓ Cost of transformers
- ✓ Labour cost

Cost of conductors

The cost of conductors can be reduced by using small section conductors and reducing the number of conductors. When selecting a conductor to be used, electrical characteristics of each conductor are considered but other factors such as the voltage levels and voltage drop, the insulators, weather and geographical location are considered. According to [Gaunt, 2003], 6/1 Aluminium Conductor Steel Reinforced (ACSR) was used for MV distribution, All Aluminium Alloy Conductor (AAAC) is used in areas exposed to corrosion and ¾ ACSR conductors have been used for longer spans. Nowadays, single phase is used for small loads but three phase systems can also be used depending on the size of the load.

Cost of structures

The cost of structures is an important factor to be taken into account during rural electrification costing. There are mainly three different types of poles used: metallic poles, concrete poles and wooden poles.

- Metallic poles are mainly used for HV transmission lines and in urban areas. Due to their high cost, they are not favourable for rural electrification applications.
- Concrete poles are used in many countries despite their high cost. But their durability and cheaper fittings made them justifiable [Gaunt, 2003].
- Wooden poles are currently used in many developing countries. Their advantages over the other types of poles are their low cost, light weight and easy to handle. These made them to be useful for rural electrification [Gaunt, 2003]. Wooden poles are currently the most used in Rwanda for LV and MV networks in remote areas [Mininfra, 2010].

Cost of transformers

The cost of a transformer depends on its size and the type of distribution technology used. A proper design of the load to be supplied should help in reduction of the transformer cost by selecting an appropriate size of the transformer.

Labour cost

The labour cost is an important factor because it affects the overall cost of the project. In countries where labour costs are high, rural electrification projects become more expensive.

Table 2-8 shows the difference between electricity distribution technologies based on cost, number of conductors, number of poles, number of insulators and the span length [Gaunt, 2003].

Table 2-8: Relative feeder efficiency, based on estimated costs, for 10% volt drop

Source: Gaunt, 2003

Line type	**3-ph+N**	**3-ph**	**2-ph**	**Ph+N**	**SWER**	**Bi-ph**
No of conductors	4	3	2	2	1	3
No of phases	3	3	2	1	1	2
Span length [m]	80	100	140	140	210	100
Conductor/km [m]	4000	3000	2000	2000	1000	3000
Poles/km	12.5	10	7.1	7.1	4.8	10
Insulators/km	37.5	30	14.3	7.1	4.8	10
total cost/km [US$]	12125	9500	6286	5929	3619	9000
Relative cost/km	1.28	1	0.66	0.62	0.38	0.95
Relative power	1	1	0.58	0.17	0.3	0.67
Relative MW.km/cost	0.78	1	0.87	0.27	0.8	0.7

2.7 Voltage regulation and reliability

In order to make sure that accurate load models and correct conductor sizes are used, different methods can be used. For the purpose of the cost reduction, design parameters are sometimes scaled. Deterministic and probabilistic methods have been used for residential load modelling but these methods have been proved to be ideal after discovering that the loads for all customers can be modelled as constant current loads [Schalk et al, 2002]. According to [Ferguson and Gaunt, 2003], the standard voltage currently used for households is 230V. The voltage regulation constraints affect distribution networks especially those used in rural electrification [Brown and Gaunt, 2002]. The voltage regulation and reliability can be well addressed by using appropriate technologies, correct conductors and voltage levels [Schalk et al, 2002; Gaunt and Herman, 2005; Dagbjartsson et al 2007; and Brown and

Gaunt, 2002]. For this reason, the recommended voltage regulation of 10% is allowed for LV.

For a proper network design, the voltage drops in both MV and LV lines should be kept to small values. There is a possibility to use one MV/LV distribution transformer but this results in large conductors sizes of LV line. Another option is the use of many small MV/LV transformers and keep the LV conductor size small [Schalk et al, 2002 and Brown and Gaunt, 2002].

2.7.1 Voltage drop calculation in LV feeders

According to [NRS 034-1, 2007], the voltage drop depends on how consumers are connected to the line. Different patterns can be used and normally up to four (4) consumers can be connected to a phase using one clamp [NRS 034-1, 2007]. The following configurations can be used:

- ✓ Cyc mmm
- ✓ Cos mmm
- ✓ Bal mmm

Cyc refers to cyclic assignment: red, white, blue, red, white, blue...

Cos refers to cosine assignment: red, white, blue, blue, white, red,...

Bal refers to balanced and here equal number of consumers are connected to each phase at every node and m is the number of consumers connected to the same point. The main purpose of voltage drop calculation is to ensure that accurate design procedures are followed and the correct materials, which conform to the required parameters, are used [Sellick and Gaunt, 1995]. Many methods and procedures can be used to calculate the voltage drop in a feeder. According to [Sellick and Gaunt, 1995], the following flow chart can be used to show the methods and procedures followed in Voltage drop calculation.

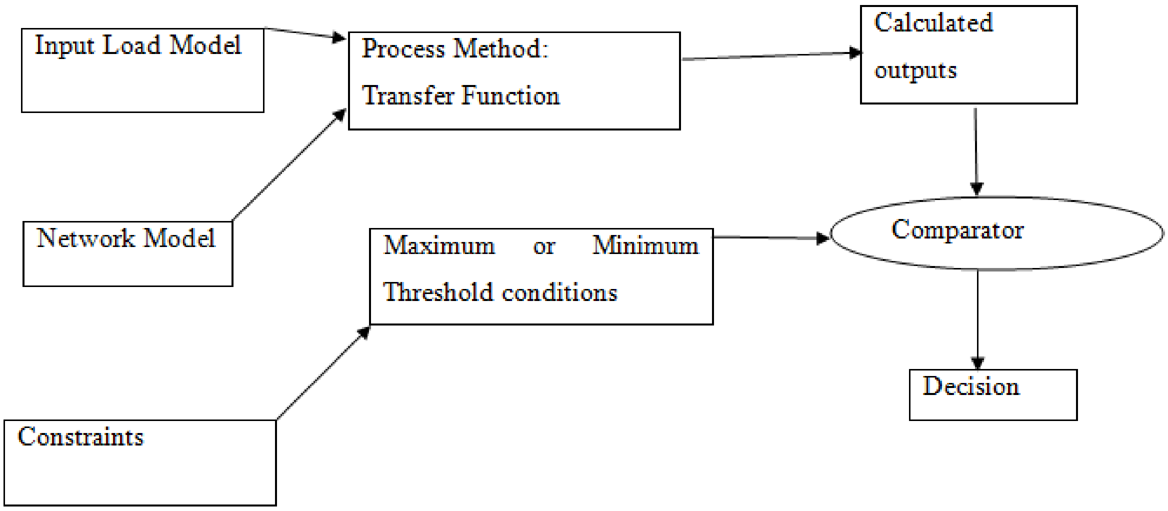


Figure 2-4: Voltage drop calculation flow chart

The definitions of the flow chart components are as given by [Sellick and Gaunt, 1995].

Input load:

This is an indication of the After Diversity Maximum Demand (ADMD) of the consumers. Load models are treated as homogeneous, typical residential loads

Network model:

The parameters of the load model are consumer phases, conductor resistance source voltage and the network configuration.

Process method:

The process is composed of the physical network and the transfer function which includes conductor resistance, source voltage and the network configuration.

The process depends on the type of network configuration, in any case it can be bi-phase, three-phase three-wire.

Calculated outputs:

The model will evaluate the inputs and give an output which is either a voltage or voltage drop. The voltage drop given is an indication of how efficient and reliable the system is.

Constraints:

The network constraints are:

- ✓ Voltage regulation of 10% of 230V.

- ✓ Selection of the conductors to be used in the feeder, putting into consideration the thermal rating of the required.
- ✓ Cost of losses due to non-zero resistances of the distribution conductors.

Threshold conditions:

These are acceptable levels or standard values which the comparator compares with the output.

2.7.2 Load modelling and load forecast

One of the most important aspects in planning a transmission or distribution network is the load modelling. Inaccurate modelling leads to under or over design of the networks and this defeats the technological objectives of utilities which is to develop appropriate networks at a minimum cost [Gaunt, 2003]. The load modelling and forecasting help the utility companies to make important decisions on purchasing and generating electric power, load switching and infrastructure development.

The load forecast must give sufficient information about how much power is to be delivered to specific customers, especially considering the After Diversity Maximum Demand (ADMD) of the customer [Gaunt, 2003]. For short term load forecast, several factors such as time factors, weather data and possible customers' classes should be considered. The medium- and long-term forecasts take into account the historical load and weather data, the number of customers in different categories, the appliances in the area and their characteristics including age, the economic and demographic data and their forecasts [Gaunt, 2003].

2.7.3 Load forecast techniques and electrification model design

There are many techniques developed to solve the load forecast problem. Most of them use artificial intelligence to solve those problems [Bansal and Pandev, 2005]. However, deterministic and probabilistic load model methods are the two methods to which deep researches were done to determine which is the most effective [Schalk et al, 2002].

Monte Carlo simulation method

The voltage drop is calculated using customer currents drawn from customers randomly [Sellick and Gaunt, 1995].

Single parameter methods

Using this method, a balanced voltage drop is calculated and the value is adjusted by empirical factors to compensate for unbalance of load and diversity [Sellick and Gaunt, 1995]

Multiple parameter methods

This is derived from Monte Carlo simulations where the calculated voltage drop is adjusted to compensate the unbalance of load and diversity. The factor used in correcting the unbalance of loads is obtained for simulations [Sellick and Gaunt, 1995].

Statistical methods

In these methods, statistical probability and analytical derivation are used to calculate the voltage drop within a defined confidence [Sellick and Gaunt, 1995].

Deterministic method

Deterministic method involves the use of after diversity maximum demand (ADMD) to determine the load currents in a feeder at a maximum demand. Diversity and voltage unbalance are corrected by correction factors [Brown and Gaunt, 2002]. Since rural feeders are normally associated with few customers, the uncertainties of using correction factors increases. The correction factors affect the sizing of loads and the voltage drop of the feeders [Ferguson and Gaunt, 2003].

Probabilistic method

A probabilistic design method based on the Beta probabilistic density function (pdf) was proved to be more accurate [Herman and Gaunt, 2008]. This approach estimates the Beta parameters from ADMD of the customers. The Herman Beta method gave conclusion to the fact that loads were normally distributed and domestic loads can be modeled as current loads [Gaunt, 2008] and [Schalk et al, 2002]. Probabilistic model uses the beta probability distribution function known as beta pdf [Ferguson and Gaunt, 2003; Schalk et al, 2002], to look into the uncertainties associated with loads [Gaunt, 1996]. In order to obtain accurate designs and system reliability, customer data, especially load must be collected and analyzed through the use of statistical functions [Schalk et al, 2002]. According to [Herman and Gaunt, 2007], the probabilistic load uncertainty and load parameter uncertainty can be separated as this is helpful in analyzing customer loads.

The extensive researches and analysis of the customer data collected has led to a conclusion that consumer data can be represented using a histogram [Herman and Maritz, 1996]. The histogram has a mean (μ), standard deviation (σ), maximum and minimum of consumer load current [Cross et al, 2006]. A survey [Schalk et al, 2002] was conducted in Tambo community, South Africa, where the average income and loads of the households were obtained. It was discovered [Schalk et al, 2002] that the more varied the customer loads are, the wider the standard deviation can be. The loads, at a 5 minute period, are analyzed probabilistically to determine the voltage drop in a feeder [Herman and Gaunt, 2008]. Depending on the number of customers in a particular area, the values of *α*, β and c need to be selected carefully to ensure good results. C is the scaling factor, which is the rating of the circuit breaker [Ferguson and Gaunt, 2003].

According to [NRS 034-1, 2007], the table below is used for classification of domestic consumers and it shows their typical load parameters.

Table 2-9: Classification of domestic consumers-Typical design load parameters for domestic consumers.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Current type			Load parameters – 7 years[c d e f]						Load parameters – 15 years[c d e f]					
Consumer class	AMPS[a] and LSM[a] class	Income range[b] (gross R/month)	*a*	*b*	*c*	ADMD kVA	*μ* A	*ó* A	*a*	*b*	*c*	ADMD kVA	*μ* A	*ó* A
Rural settlement	LSM 1 (low end)	0 to 600	0,30	2,98	20	0,42	1,83	2,78	0,35	2,88	20	0,50	2,17	3,03
Rural village	LSM 1 and 2	400 to 900	0,43	2,52	20	0,67	2,91	3,55	0,48	2,13	20	0,84	3,65	4,07
Informal settlement	LSM 3 and 4	800 to 1 500	0,77	9,88	60	1,00	4,35	4,56	0,91	8,80	60	1,30	5,56	5,36
Township area	LSM 5 and 6	1 500 to 3 000	1,05	7,81	60	1,64	7,13	6,18	1,22	5,86	60	2,37	10,30	7,96
Urban residential I	LSM 7	3 000 to 5 500	1,23	5,56	60	2,50	10,87	8,28	1,25	3,55	60	3,59	15,61	10,93
Urban residential II	LSM 7 and 8	5 500 to 8 500	1,45	6,07	80	3,54	15,39	10,81	1,42	4,10	80	4,72	20,52	13,68
Urban township complex	LSM 8	8 500 to 12 000	1,45	5,75	80	3,70	16,09	11,20	1,42	4,13	80	4,70	20,43	13,63
Urban multi-storey/estate[f]	LSM 8 (high end)	12 000 to 24 000	1,43	4,41	80	4,50	19,57	13,15	1,37	3,39	80	5,30	23,04	15,09

For a residential load, the maximum demand can be calculated using the following formula as shown by equation 2.2 below [NRS 034-1, 2007]:

$$L = \frac{0.23 * N * c}{(a+b)*(a+1.28*\sqrt{\frac{a*b}{N*(a+b+1)}})} \qquad (2.2)$$

Where: a, b and c are the values of alpha, beta and circuit breaker size respectively. L is the load in kilovolt Amperes (kVA) and N is the total number of households.

The ADMD is measured by a single data logger at a substation. The values Herman Beta parameters are measured for different customers [Herman and Gaunt, 2007; D.Thirault et al, 2002]. Some of the methods like Monte Carlo, single and multiple parameter methods, deterministic method and statistical methods are still in use but to a lesser extent. More emphasis has been put on the Herman Beta method because of its accuracy and proved efficiency [Sellick and Gaunt, 1995].

2.8 Electricity usage in rural communities

The purpose of this research is the supply of electricity to rural households, the main step is to estimate the electricity usage for a rural household. The justification is needed while choosing the rural household electricity consumption. According to NRS 034-1 [2007], the ADMD for a household in a rural settlement in South Africa was 0.42kVA whereas for a rural village, this value increases to 0.67kVA depending on their level of income. According to [Johnson Pfaira, 1998] as shown in table 2-10, with emphasis on PV technology, the daily electricity power consumption depends on the customer income in Sub-Saharan Africa.

Table 2-10: Daily electricity usage for rural households

	Low income	Medium income	High income
% of population	60%	35%	5%
Daily electricity consumption	0.1kWh	0.2kWh	0.5-0.7kWh

Electricity consumption in rural areas is mainly for lighting and powering radios. Some rural households may have TV sets, fridges or any other household appliances but this is not very common in rural areas. According to [Smail Khennas et al., 2000], the rural loads for mini-hydropower projects developed in Sri-Lanka vary between 100W and 200W per household.

2.9 Electricity usage for a rural household in Rwanda

According to Rwanda Energy Water and Sanitation Authority report [RECO-RWASCO, 2009], the rural household electricity usage in Rwanda was estimated to 27W, 141W and 595W for Low, medium and high income rural households. These estimates were based on income levels of the rural populations as shown in table 2-11

Table 2-11: Typical village loads in Rwanda

Income	**Equipment installed**	**Quantity**	**Capacity**	**Usage/day**		**Energy consumption**		**Peak power**
			W	From-to	hrs	kWh/month	kWh/yr	W
Low	CFL lamps	3	9	6 to 10	4	3.3	39	27
	Total annual consumption and peak demand per household					**3.3**	**39**	**27**
Medium	CFL lamps	4	9	6 to 10	4	4.4	53	36
	Radio	1	50		6	9.1	110	50
	CD player	1	55		2	3.3	40	55
	Total annual consumption and peak demand per household					**17**	**202**	**141**
High	CFL lamps	5	9	6 to 10	4	5.5	66	45
	Radio	1	80		10	24.3	292	80
	CD player	1	110		2	6.7	80	110
	TV Colour 20"	1	110		4	13.4	161	110
	Fridge	1	250		6	45.6	548	250
	Total annual consumption and peak demand per household					**96**	**1146**	**595**

Source: [RECO-RWASCO, 2009]

To be more realistic and considering the increase in consumption that is expected due to electrification, the rural household electricity consumption in a typical rural area of Rwanda was estimated as shown in table 2-12 below.

Table 2-12 Estimates of rural load in Rwanda

Item	**Quantity**	**Power/Unit [W]**	**Total power [W]**
Lamps	4	40	160
Radio	1	80	80
CD player	1	50	50
TV	1	110	110

According to table 2-12, the total power per household to be used in this study is taken as 400W. The total power consumption per village can be obtained by multiplying the individual household power consumption by the total number of households per village. For the purpose of the network design and in order to find the design parameters required for voltage drop calculations in LV feeders, the ADMD of a household should be obtained.

Assuming the power factor of 0.95, the ADMD is given by equation 2.3 below:

$$ADMD[kVA] = \frac{400W}{0.95} = 0.42kVA \qquad (2.3)$$

2.10 Summary

Chapter 2 has discussed electrification in Rwanda and the hydropower technology in general. It was found that electrification level in Rwanda is still very low as only 10% of the population has access to electricity and the rural areas are still behind because this percentage falls to less than 2%.

The production of electricity is mainly hydro because of the potential in rivers that can be developed for hydropower plants. Due to this, the government of Rwanda has included small, mini and micro hydropower resources in the programme aimed at increasing access to electricity countrywide. A number of micro and small hydropower plants under development until 2013 was shown and this will help to increase access to electricity in both rural and urban areas of the country.

The review of literature on hydropower technology has shown the meaning of hydropower, its main components and its role in electricity production worldwide. Figure 2-2 show that hydroelectricity has an important role in electrical energy in this world and China and Canada come in the first place in hydropower plants development.

The classification of hydropower plants was found to be based on the size but there is no standard regarding this classification. The terminology to be used in this study refers to the classifications according to European Union as stated by [Williams and Porter, 2006]. The cost of development of hydroelectric power plant was found to vary according to the site and the type of equipment used.

The high costs are mainly due to terrain structure which causes the civil work to cost a lot during the power plant construction. Small and micro hydropower developments normally involve high costs but the use of locally manufactured equipments as done in Sri-Lanka, Nepal and China helps to reduce the cost considerably.

Different costs are found from the literature and the selection of the cost to be used in this study was done based on the costs of similar projects currently under execution in Rwanda. The development of hydropower resources for rural electrification was found to be the best option where hydro resources are available and this is the case in China, Nepal, Vietnam and Sri-Lanka.

Different technologies used in rural electrification were discussed and evaluated based on their advantages and disadvantages. As the least cost technology and acceptable network reliability are the requirements of the distribution network, design parameters have been selected for the network design in this dissertation.

This chapter has also discussed electricity usage in rural communities. It was found that the level of income influences the use of electricity. For the case of Rwanda, an approximate power of 0.4 kW and ADMD of 0.42kVA were used as the typical rural household load. This value will be used in voltage drop calculations in LV feeders using Herman beta pdf spreadsheets.

Another issue to be considered is the cost of the distribution systems. In rural electrification projects, the cost reduction and the reliable power supply are the main constraints. For this, accurate network design and the selection of conductors to be used for MV and LV distribution lines are the main concerns.

The selection of conductors for LV network can be done by calculating the voltage drops in LV feeders. Using Herman beta pdf spreadsheets and different LV distribution technologies helps to determine the appropriate type and size of conductor that fulfils the network requirements at a low cost.

3 THEORY DEVELOPMENT

3.1 Introduction

This chapter aims at developing the concepts to be followed for the design of the rural electrification network. The impact of the population density on total LV length is shown and will be applied in rural distribution network model design.

3.2 Effect of population density on LV network length

The impact of the population density on rural electrification projects should not be neglected while planning a rural electrification programme. The population density affects the network design in rural areas because of the dispersion of households. To account for this, this part of the thesis aims at developing a way of estimating the relationship between the population density and the LV network length required to connect the households in rural areas of Rwanda. This concept is based on the Minimum Spanning Tree problem (MST). Matlab was used to develop the code used for calculating the minimum LV distance required to interconnect rural households arranged in a random manner inside a selected area. The optimization of the LV rural network carried out here intends to get the minimum length of the LV network to interconnect all households presented in a given area and it involves the following steps:

- Random coordinates generation
- Calculation of inter-household distance
- Find the distance matrix
- Calculation of the shortest path to interconnect the households

3.2.1 Random coordinates generation

As there is no rule governing the location of households inside a village, this study approached this problem by considering rural households to be randomly located inside a village. Taking into account the low population densities found in most of the rural areas, specifically in Rwanda as mentioned in section 2.3.1, Random coordinates between 1 and

100 representing the number of households are generated. Random coordinates are generated from the random number generator.

The following function was used: XY=randint(n,2,[0,100]) to get the values of XY coordinates. The numbers of points generated represent the household's density. n here represents the number of households and 2 represents the number of columns which contain X and Y values.

Example: XY=randint(5,2,[0,100])

This function generates 5 random coordinates using the numbers between 0 and 100. Here, 2 means the number of columns. The output of this function in matlab shows the following:

```
XY =

    58     1

     6     4

    23    17

    35    65

    82    73
```

The above generated coordinates represent the location of households and they can be used to find the distances between these households.

3.2.2 Inter-household distance

In order to get the shortest path to interconnect all the points, distances between each point and all the others in the set should be known. The following function was used in order to find these distances: A=pdist(XY). The resultant distances are shown below and are ordered as from the above shown coordinates. This is a row matrix generated using the above shown function and it shows a pair of distances between each point and other points in this set.

```
A =

52.0865   38.4838   68.0074   75.8947   21.4009   67.5426  102.6499   49.4773   81.3449
47.6760
```

From these distances, it is now possible to find the shortest path to interconnect the 5 points (households). The procedure to find this shortest interconnection is through the distance matrix.

3.2.3 Distance matrix

The distance matrix is the key input for the process of getting the minimum spanning tree. It is the matrix that shows every single distance between all the nodes (These nodes represent the households for our case). From the above coordinates and distances, the following is the resultant distance matrix:

B =

0	52.0865	38.4838	68.0074	75.8947
52.0865	0	21.4009	67.5426	102.6499
38.4838	21.4009	0	49.4773	81.3449
68.0074	67.5426	49.4773	0	47.6760
75.8947	102.6499	81.3449	47.6760	0

From the distance matrix generated from the algorithm shown in ANNEX 1, all the distances as well as the figure representing the inter-households distances can be obtained as follows:

(2,1)	52.0865
(3,1)	38.4838
(4,1)	68.0074
(5,1)	75.8947
(3,2)	21.4009
(4,2)	67.5426
(5,2)	102.6499
(4,3)	49.4773
(5,3)	81.3449
(5,4)	47.6760

These are the respective distances between different nodes as numbered from 1 to 5.

This representation can be well shown in figure 3-1.

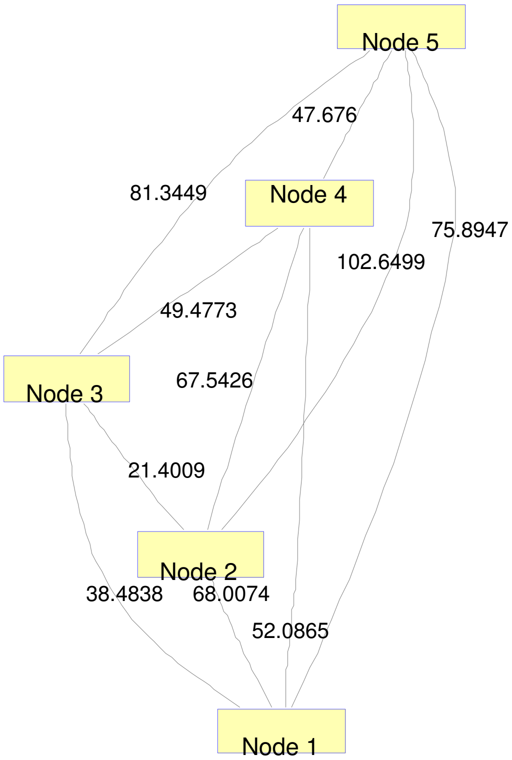


Figure 3-1: Distances between the nodes (households)

From figure 3-1 as shown above, it can be deduced that the shortest path to interconnect all the nodes by developing an algorithm to find the minimum spanning tree.

3.2.4 The minimum spanning tree

Figure 3-1 shows all the possible distances between 5 households. From these distances, it is possible to develop an algorithm that would be used to calculate the shortest path convenient to interconnect our 5 households. This shortest path is commonly called the minimum spanning tree problem.

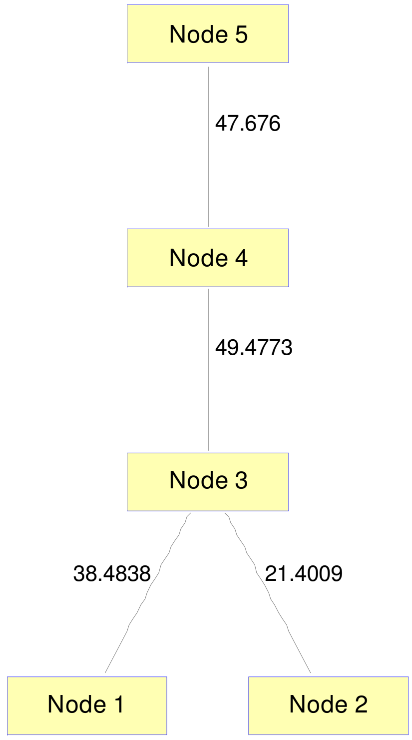


Figure 3-2: Shortest path to interconnect 5 households

The minimum total length that is needed to interconnect all these households can be calculated by adding all the shortest paths in this graph as shown by the algorithm in appendix A.

The simulation of the same number of households results in slightly different figures because of the random nature of household's distribution. Doing this for various numbers of households gives the approximation of how the population density in rural areas affects the distance between households and therefore the total LV network required in case of electrification.

The following table shows the results of 10 iterations simulated for different population densities.

Table 3-1: Population density Vs LV network length

Density	Minimum LV network length [*10m]										Average [*10m]
HH/km2	It 1	It 2	It 3	It 4	It 5	It 6	It 7	It 8	It 9	It 10	
5.0	184.1	175.7	149.0	171.5	87.5	149.8	154.2	125.5	105.6	172.8	147.6
10.0	256.8	207.3	263.5	202.9	145.9	178.4	190.9	227.6	211.0	225.2	210.9
15.0	282.8	290.0	251.3	246.7	261.4	217.7	238.0	234.0	249.2	274.2	254.5
20.0	278.7	304.9	338.6	315.8	290.4	298.6	295.2	269.5	286.3	325.7	300.4
25.0	369.6	381.7	341.5	327.1	381.7	364.4	302.7	364.9	328.6	316.7	347.9
30.0	391.1	417.6	398.4	341.0	426.7	413.4	397.1	349.9	369.4	361.4	386.6
35.0	429.4	385.9	396.3	377.1	400.2	408.7	407.5	410.2	406.0	393.6	401.5
40.0	486.6	420.2	459.8	445.8	452.7	409.2	398.1	440.6	420.2	463.1	439.6
45.0	446.9	437.5	453.1	468.1	501.9	469.7	497.5	477.1	465.1	434.8	465.2
50.0	474.9	490.4	444.1	492.8	482.3	469.2	518.3	470.4	498.5	490.1	483.1

Table 3-1 shows the values obtained by successive simulations for 10 different population densities. Each density was simulated in ten iterations and the resulting shortest distances to interconnect the nodes are shown. From these results, a graph showing the rate at which LV network length changes with increase in population density was deduced.

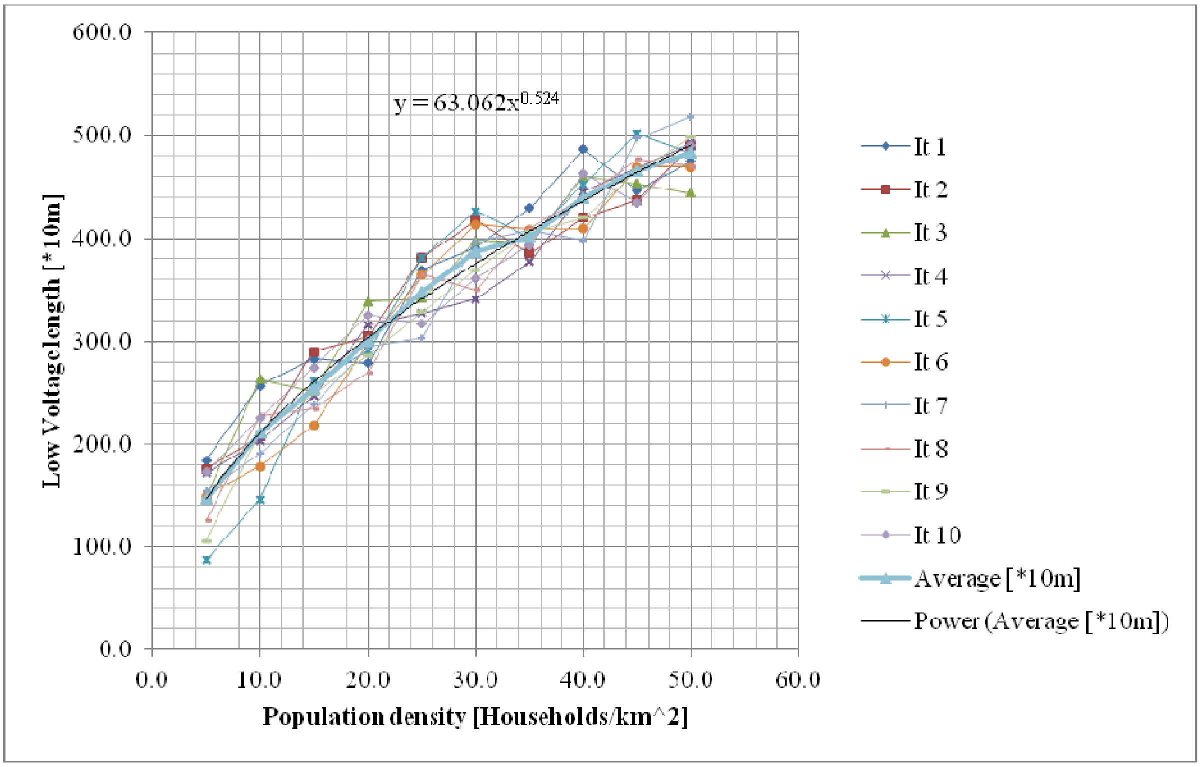


Figure 3-3: Relationship between population density and Low Voltage network length

$$y = 63.062 * x^{0.524} \qquad (3.1)$$

For more details about the procedure and functions used to find these values, the matlab code developed for the calculation of the minimum distances as well as the details about the distance matrix are shown in Appendices A and B. The interpretation of figure 3-3 can be clearly done by showing the relationship between the population density and LV network length required to connect each household.

Equation y= 63.06x^0.524 shows that as the population density increases, the required total LV network also increases. But as shown in figure 3-4 below, the average LV network to connect an individual household reduces as the population density increases.

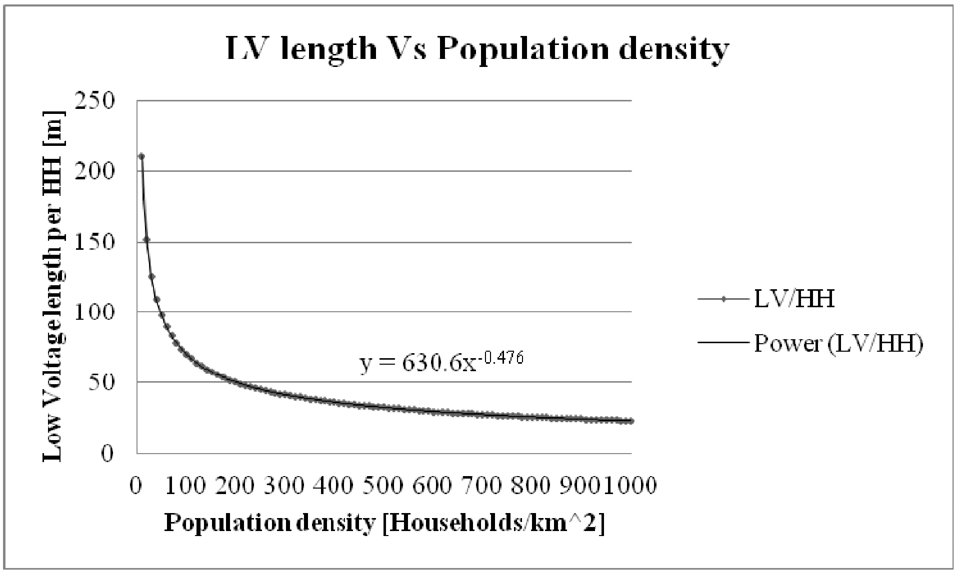


Figure 3-4: LV per household Vs population density

As shown in figure 3-4, it is clear that as the density increases the average LV line required to connect a household becomes short. This relationship between the population density and the LV line length as shown by equation 3.2 will be used in calculation of LV lines for different villages.

$$y = 630.6 * x^{-0.476} \qquad (3.2)$$

3.3 Summary

Chapter 3 has discussed the impact of the population density on LV distribution network length. It was shown that as the population density reduces, the average distance between rural households increases, therefore resulting in longer LV lines to interconnect the households. The increase in population density causes the reduction in average distance between households.

The relationship between the population density and LV network length was established. This relationship is the basis of the rural distribution network design for different population densities in rural areas of Rwanda as it will be discussed in chapter 4.

4 CASE STUDY: RURAL ELECTRIFICATION IN RWANDA

Chapter 3 has established the relationship between the population density and the LV network length. Chapter 2 has reviewed the theory related to rural electrification technologies, the design parameters required for a rural distribution network and the typical power consumption for a rural household. This part of the study aims at using the techniques mentioned in chapter 2 and the relationship shown in chapter 3 to design a rural distribution network in Rwanda. The design of LV and MV network is carried out by applying the voltage drop calculation methods. The selection of the LV distribution network to be used will be based on the findings from the requirements of Bi-phase and single phase voltage drops as well as the size and number of MV/LV transformers required. From this, the MV network will be designed according to the requirements of LV network.

4.1 LV and MV network

This is a major consideration in this project because of the wide dispersion of the rural population. Despite the fact that transmission and distribution do not constitute direct costs of electricity generation, they must be considered in this comparison in order for the comparison to be done on an equal basis. Figure 4-1 shows how the cost of electricity varies with the length of transmission and distribution lines.

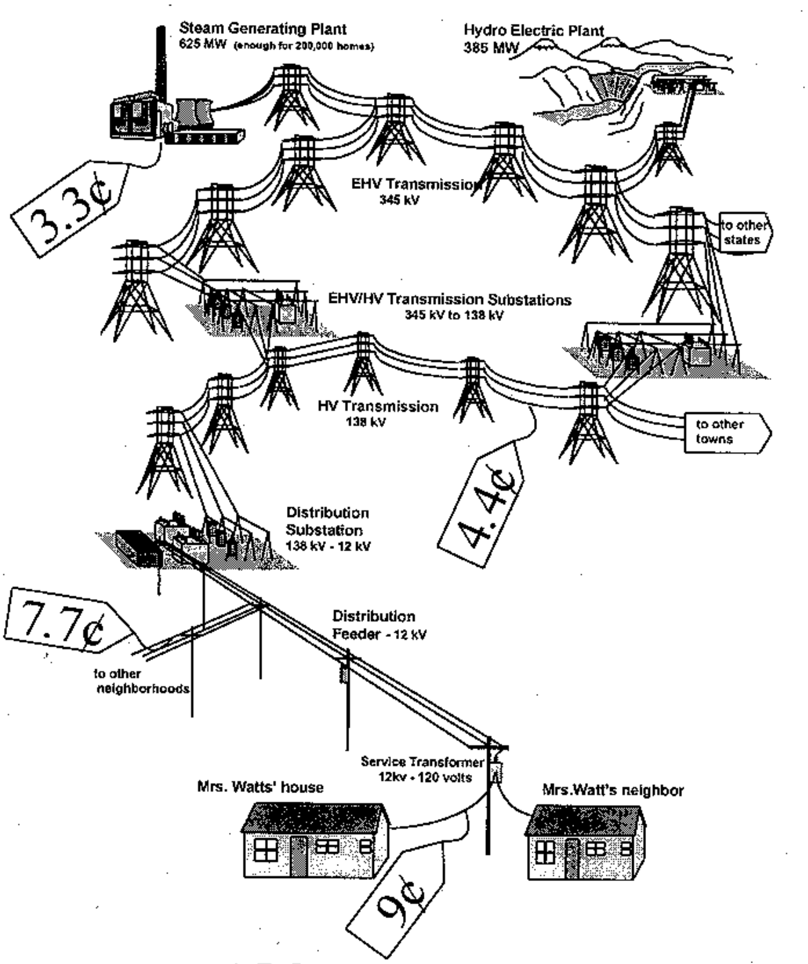


Figure 4-1 Cost increase with variation of the distance from the generating plant

Source: Philipson et al., 1998

Figure 4-1 above shows how the cost in US cents increases as the distance between the generation plant and the final consumer increases. The same thing in our analysis, the increase of the MV and LV length for the distribution lines causes the overall cost of rural electrification to be high.

The difficulty here was the variation of the population density in different regions of the country so that the assumption of an **average** population density was avoided. According to Markku Hyvärinen [2008], geographical dispersion of customers is one of the most distinctive cost-drivers in electrical networks.

Nearly all comparative methods use the length of the network especially in relation to the number of connections or customers to describe the environment. For this reason, the further away the customer, the longer the feeder.

What was considered to be more useful is to consider three different population densities to highlight the impact of the population density on rural electrification projects. The population densities in the northern, western and southern provinces of the country were provided by the National Institute of Statistics of Rwanda [NISR, 2002].

The calculation of distribution requirement was done by modelling 98 villages (as previously calculated) as being horizontally distributed across the region in a linear grid arrangement. The area of one grid square in km^2 was calculated by multiplying the number of people in the village by the typical household size and dividing by the population density in persons per km^2. This is the area inhabited by the villagers if they were evenly spread out across the countryside.

From this, the distance between the villages in the model can be calculated. The average number of people per household in Rwanda was obtained from the National Institute of Statistics of Rwanda report [NISR, 2002] where 5 people are the average per household in the country. This is in accordance with Bongaarts [2001] from the population survey conducted in 43 countries where an average of 5.2 people per household was found to be the approximate figure.

The following is the village spacing model which takes into account the rural population density, the household size and the village size.

$$A = \frac{N * S}{D} \qquad (4.1)$$

$$C = \sqrt{A} \qquad (4.2)$$

Where:

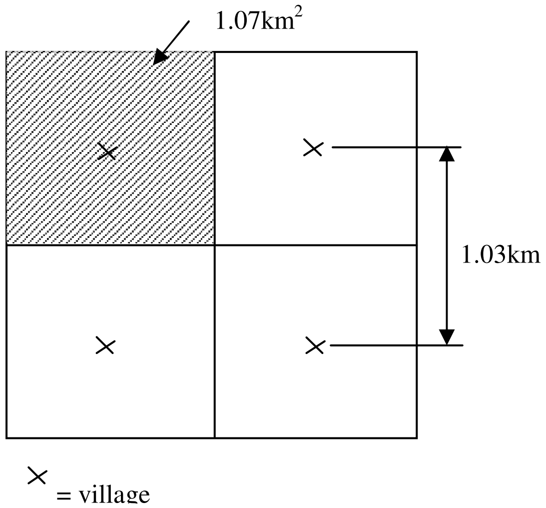
A is the proportioned area

N is the village size (Number of households)

S is the household size (The number of people per household)

D is the population density within the selected area

C is the side of the square



E.g.

Village size = 96 households

Household size = 5 persons

Population density = 425/km²

Proportioned area = $\frac{96 \times 5}{425} = 1.07km^2$

Assuming that the village is a square, its side is given by: $= \sqrt{1.07} = 1.03km$

Figure 4-2: Example of the village spacing model

4.2 Types of villages

This rural electrification model takes into account three (3) different types of villages due to different population densities in rural villages of Rwanda as illustrated in section 4.1. Table 4-1 shows the data used for village sizing. Three different types of villages are taken from different provinces of Rwanda.

Table 4-1: Population density in rural areas of Rwanda

Province	**Density [Inhabitants/ km²]**	**Population of the village**	**Village size [Households]**	**Village area [km²]**	**Side of the village [km]**
Ruhengeli	425	480	96	1.1294	1.06
Gisenyi	325	375	75	1.1609	1.08
Kibuye & Gikongoro	100	185	37	1.8137	1.3

According to these population densities and using the village spacing model as shown in section 4.1, the size of the village can be obtained by dividing the density by the number of people per household. In the same manner, the proportioned area of the village can be obtained. Then, assuming the village to have a square form, its side is obtained by the square root of the area. These different sizes of villages are useful while dealing with LV and MV distribution lines in section 4.3 to section 4.7of this thesis.

4.3 Hydropower options and number of schemes required

As this thesis aims at comparing the costs of rural electrification of 98 villages in Rwanda using mini and small hydropower technologies, it is necessary to define the total power required by each village and estimate the size of mini hydro technology to be used. Table 4-1 provides the number of households per village. From this data and considering the power consumption of a typical rural household in Rwanda as established in section 2.9, the total power per village can be deduced. Table 4-2 shows the total power required by each village.

Table 4-2: Power consumption per village

Village Type	Small	Medium	Large
Village size [Households]	37	75	96
Power consumption per household [kW]	0.4	0.4	0.4
Total power per village [kW]	14.8	30	38.4

4.3.1 Number of villages and hydropower schemes requirement

The selection of mini hydropower schemes required depends on the total number of villages. The total number of villages was obtained by setting the goal of providing electricity to around 5,000 rural households using mini and small hydropower schemes. These 5,000 rural households are located in different villages in rural areas of Rwanda.

As villages are classified as large, medium and small; in order to get the approximate number of 5,000 rural households, the number of villages in each category can be estimated. The determination of the number of villages per category is based on the estimation that in rural areas, there are a large number of small villages, few medium villages and a small number of large villages. Based on this, 68 small, 20 medium and 10 large villages were used.

The total number of households in these 98 villages is 4,976 households. To determine the size of a mini-hydro scheme required, it was assumed that at least three (3) large villages should be supplied by a single mini-hydro scheme in order to have a decentralized type of supply intended by mini-hydropower development in rural areas. The 3 village's power consumption is equal to 400W*96*3=115.2kW. Based on this fact, 130kW was chosen as the appropriate size of a Mini-hydropower plant required.

Table 4-3: Number of mini-hydro schemes required

Village type	No. of villages/ 130kWscheme	No. of schemes
small	8	9
medium	4	5
large	3	3
		17

From the village size and power consumption per village established in table 4-2 and considering a mini hydropower scheme, table 4-3 shows that 17 schemes having 130kW each are required for electrification of 4,976 rural households grouped in 98 small, medium and large villages in Rwanda. The total power needed to supply 4,976 rural households is equal to 1,990.2kW. As this option requires longer MV distribution lines, a small hydropower plant of 2.5MW was estimated to be a good size for this type of centralized hydropower supply.

4.4 Voltage drops calculation

The selection of appropriate conductors size for LV distribution lines requires the calculation of the voltage drops in LV feeders. This was done by using Herman Beta pdf spreadsheets. The following parameters must be known for voltage drop calculation using Herman beta pdf spreadsheets:

1. The supply voltage: For the rural areas in this study, the supply voltage is 230V.

2. The load parameters a, b and c. These parameters can be found from ADMD of a rural household. For ADMD of 0.42kVA and c=20 as used in this analysis, a=0.355 and b=3.536.

3. Number of consumers per node. This number may vary from node to node as rural populations are arranged in a random manner. For the purpose of this study, 3 different villages' sizes were used where the numbers of households per village are 37, 75 and 96

respectively. The average LV network length per household can be obtained as stated in chapter 3. Using equation (3), for the large village of 96 household, the average LV per household was found to be 72m. For the voltage drop calculations, this figure was used and due to a random distribution of households in rural areas, average numbers of 3, 4 and 5 consumers per node were adapted.

4. The number of nodes required to reach 96 households is 24 nodes as per equation 3.

5. Resistance of conductors: Different sections of ABC overhead conductors were used.

6. The design risk value: 10%.

Two different LV network (bi-phase and single-phase) and 4 types of ABC (Aluminium Bundled Conductors) conductors were used for the voltage drop calculation in LV feeders.

4.5 Bi-phase and single phase LV voltage drops

This section shows the results of the voltage drop calculation for bi-phase and single-phase LV network feeders. Herman beta pdf spreadsheets have been used to calculate the voltage drops in LV feeders using different sections of ABC conductors. The bi-phase and single phase have been selected because of the nature of loads to be supplied and in order to minimize the cost of the network.

4.5.1 Bi-phase voltage drops

The following configuration was used for the voltage drop calculations. In this case, households are connected to two phases of the LV network as shown in table 4-4.

ma is the number of households connected on a specific node of phase a.

mb means the number of households connected to a specific node of phase b.

Alpha and **Beta** parameters are the fixed values derived from Herman-Beta spreadsheets and they depend on **Cb** which is the maximum capacity of the circuit breaker in Amperes.

Table 4-4: Bi-phase voltage drop calculation using Herman beta pdf spreadsheets

	No Consumers		Load Parameters			Conductor	
Node	**Red**	**Blue**	**Alpha**	**Beta**	**Cb**	**Length**	
	ma	**mb**			**[A]**	**[m]**	**Code**
1	***2***	***1***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
2	***2***	***2***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
3	***2***	***3***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
4	***2***	***3***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
5	***2***	***2***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
6	***2***	***1***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
7	***2***	***1***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
8	***2***	***2***	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
9	**-**	**-**	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
10			***0.355***	***3.536***	***20.00***	*72*	*ABC25*
11			***0.355***	***3.536***	***20.00***	*72*	*ABC25*
12			***0.355***	***3.536***	***20.00***	*72*	*ABC25*

Table 4-4 above shows the input values to Herman beta pdf spreadsheets and the table 4-5 below shows the output in form of voltage drops. The figures in italic are the inputs and the numbers in bold as shown in table 4-5 below are the corresponding outputs. Rows 9 to 12 were used in order to show the number of households that can be connected up to the maximum allowed voltage drop. Any single connection beyond row 8 will result in the voltage drop value greater than 10%.

Table 4-5: Typical output of Herman beta pdf for bi-phase system

Results	**Red**	**Blue**	**Unit**
%-tile Vcon	**207.15**	**210.18**	V
%Volt drop	**9.94**	**8.62**	%V
%-tile Isum	**43.13**	**40.87**	A
Mean Isum	**29.20**	**27.37**	A
Stdev Isum	**10.42**	**10.09**	A

Where:

%-tile Vcon is the voltage value measured at the last node connected

% Volt drop is the percentage of the voltage drop at the last node

%-tile Isum is the total current in the phase

Mean Isum is the mean current

Stdev Isum is the standard deviation of the total current

As the random distribution of rural household was assumed, 3, 4 and 5 households were considered to be connected alternatively on different nodes as shown in table 4-4.

Repeating this procedure for different types of ABC conductors, the following results are obtained.

Table 4-6: Voltage drops and total LV distance covered by a conductor for bi-phase system using ABC conductors

Conductor type	Maximum voltage drop [%]	Numbers of HH to reach the allowable voltage drop limit (207V). 230 – 10% * 230 = 230 -23 = **207V**	Total LV distance [m]	No of transformers per 96 Households village
ABC25	**9.94**	**31**	**576**	**4**
ABC35	9.4	36	648	3
ABC50	9.07	40	792	3
ABC70	9.28	48	864	2

Table 4-6 shows the maximum allowable voltage drops, the corresponding number of households reached by LV network, the total LV distance covered by the conductor based on the average distance between households and the number of transformers that should be required to reach 96 households.

4.5.2 Single-phase voltage drops

The calculation of voltage drops in single-phase LV network using Herman beta pdf can be done by using bi-phase spreadsheet and connecting all customers to one phase per each node. The following configuration was used as shown in table 4-7.

Table 4-7: Distribution of households per nodes for voltage drop calculation in single-phase LV using Herman-beta pdf spreadsheets

	No Consumers		Load Parameters			Conductor	
Node	Red	Blue	Alpha	Beta	Cb	Length	
	ma	mb			[A]	[m]	Code
1	***3***	-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
2	***4***	-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
3	***5***	-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
4	***5***	-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
5	***3***	-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
6		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
7		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
8		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
9		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
10		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
11		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*
12		-	***0.355***	***3.536***	***20.00***	*72*	*ABC25*

Table 4-8: Single-phase LV voltage drop results

Results	Red	Blue	Unit
%-tile Vcon	**207.20**	**233.04**	V
%Volt drop	**9.91**	**- 1.32**	%V
%-tile Isum	**52.02**	**-**	A
Mean Isum	**36.49**	**-**	A
Stdev Isum	**11.65**	**-**	A

Using the same procedure as in table 4-7 above to different types of ABC conductors, the following results are obtained.

Table 4-9: Voltage drops and total LV distance covered by the conductor for single-phase system using ABC conductors

Conductor type	Maximum voltage [%]	Number of HH to reach the allowable voltage drop limit	Total LV distance [m]	No of transformers per 96 households village
ABC25	**9.91**	**20**	**360**	**5**
ABC35	9.46	22	432	5
ABC50	9.47	24	432	4
ABC70	9.68	27	504	4

In the same manner as previously done for bi-phase systems, the total number of household that can be supplied by each type of conductor to reach the allowable voltage drop limits is obtained. Depending on the type of the village, the size of transformers can be found.

4.6 LV distribution technology and conductor size selection

The selection of LV conductor and the type of technology to be used for LV distribution is based on the results shown in table 4-6 and 4-9. The factors below were considered while selecting the type of conductor. These are:

- The conductor sectional area,
- The conductor current rating,
- The Voltage drop level,
- The maximum distance covered by the conductor,
- The resultant number of transformers necessary to supply the village.

Taking into consideration the above mentioned factors, it becomes clear that ABC25 conductor is the best conductor to be selected for LV network because it meets the load requirements of the rural network and presents the minimum cost as compared to other alternatives.

In order to choose which LV distribution technology to be used, the voltage drop limits of each technology as calculated in section 4.5, and the cost of the line are the main constraints. Regarding bi-phase and single phase technologies, tables 4-7, 4-8 and 4-9 show that ABC25 conductor can be used and the constraints here are the number of conductors required by each technology and the size of transformers to be used.

For this village of 96 households, 24 nodes separated by 72m are required. According to table 4-9, the number of nodes that cover the maximum LV distance per transformer is equal to 5. For this reason, the total LV distance to cover 24 nodes can be derived as: $\frac{360*24}{5}=1{,}728m$. As the total load per village is equal to 96*0.42kVA=40.32kVA, the supply of these nodes using bi-phase would require 4*15kVA MV/LV transformers to cover the total LV distance of 1,728m. The use of single-phase would require 5*10kVA MV/LV transformers in order to cover all 24 nodes.

Taking into consideration the number of conductors in bi-phase technology and the size of transformers required as compared to single-phase LV distribution technology, single phase would be the best option for LV distribution lines to rural households.

The selection of conductor to be used in LV distribution is based on its cross sectional area and the total distance of the LV feeder to reach the allowable voltage drop limit. Emphasis is on small section conductors because of their low cost and weight and the structures required for the distribution network which are not expensive. For this reason, ABC25 conductor is selected because it is the least cost option that would meet the network requirements.

The selection can also be done by using the following table.

Table 4-10: Comparison of bi-phase and single-phase

Technology	Number of conductors	Size of transformers	Number of transformers	Total kVA	kVA per village	Excess kVA
Bi-phase	3	15kVA	4	60	40.32	19.68
Single-phase	2	10kVA	5	50	40.32	9.68

According to table 4-10 above, the increase of the number of conductors results in excess power not consumed and the increase in cost. Therefore, the bi-phase option would not be cost effective and single-phase LV distribution technology should be selected.

4.7 Number of MV/LV transformers and length of MV distribution network

The use of single-phase LV distribution technology requires 5*10kVA transformers per large village of 96 households. Table 4-11 shows the transformer requirements for the three types of villages used in this model and the figures 4-3, 4-4 and 4-5 show the arrangement of transformers within the villages. This transformers arrangement inside the village helps us to find the length of MV distribution line required per village.

Table 4-11: Number of MV/LV transformers per village

Type of village	Size of the village [No of households]	Total power [kVA]	Number of 10kVA transformers
Large	96	40.32	5
Medium	75	31.5	4
Small	37	15.54	2

As shown in table 4-11, the number of transformers required to supply the large, medium and small villages are 5, 4 and 2 respectively. Based on these numbers and the size of the villages as previously defined in section 4.2, the following set up can be used to arrange the transformers inside the villages and from there, the length of MV network required is obtained.

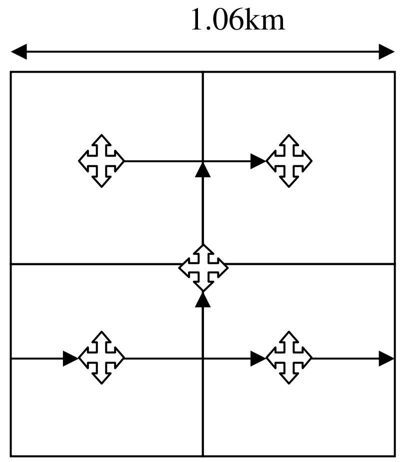


Figure 4-3: MV lines and transformers per large village (96 households)

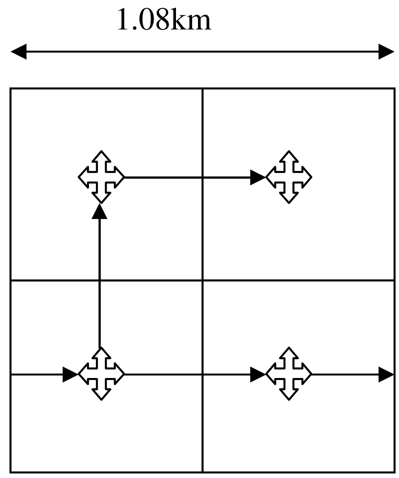


Figure 4-4: MV lines and transformers per medium village (75 households)

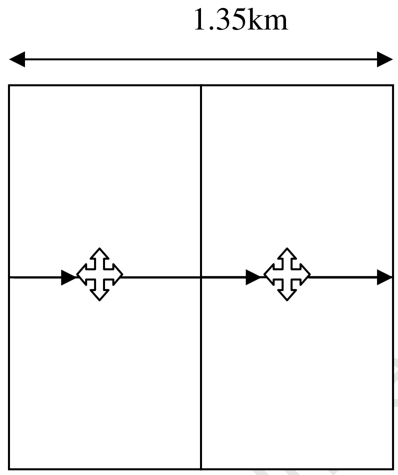


Figure 4-5: MV lines and transformers per small village (37 households)

MV/LV transformer [10kVA]

→MV line

According to positions of MV/LV transformers as shown in the figures 4-3, 4-4 and 4-5, the MV line length per village can be found as follows:

- For a large village of 96 households, the connection of 5 MV/LV transformers requires the MV line equal to 2* (1.06km/2) + 4*(1.06km/4) =2.12km.
- For a medium village of 75 households, the connection of the 4 MV/LV transformers requires 1.08km + ((1.08/2) + (1.08/2))km=2.16km of the MV line.
- For a small village of 37 households, the connection of the 2 MV/LV transformers requires (1.35km/4) + (1.35km/2) + (1.35km/4)=1.35km of MV line.

Table 4-12: MV line length per village

Village type	Required MV line [km]
Large	2.12
Medium	2.16
Small	1.35

4.8 MV network conductor selection

Case 1: Mini hydro (130kW) scheme

The selection of the conductor to be used for SWER MV distribution lines depends on the supply option. The voltage drop, being the main constraint for the conductor size selection, the following configuration was used for MV distribution network voltage drop calculations in Power World simulator.

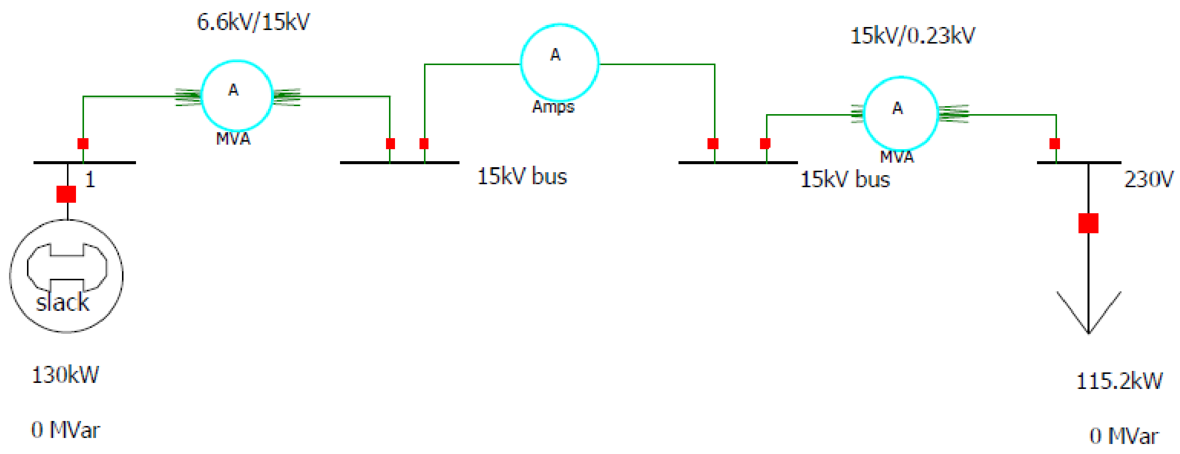


Figure 4-6: Set up for voltage drop calculation in 15kV MV line

A medium voltage (15kV) SWER line of 9km long was used for voltage drops calculations. This distance was not arbitrary chosen but it is based on the total MV line required to interconnect 3 large villages having each 96 households and is based on the supply using a Mini-hydropower scheme of 130kW. The results for 2 different sizes of bare ACSR (Aluminium Conductor Steel Reinforced) conductors are shown in table 4-13 below:

Table 4-13: MV voltage drops for ACSR bare conductor

Cross sectional area [mm^2]	Maximum voltage drop [%]
18.7	1.6
29.2	1

As shown in table 4-13 above, all the two conductor types used are in the range of the allowable voltage drop limits. In that case, the selection of the appropriate conductor depends on the cross sectional area and current rating and for that reason; ACSR conductor having 18.7mm^2 would be the cheapest option for MV distribution lines in case of mini-hydropower schemes.

Case 2: Small hydro (2.5MW) scheme

Using a single 2.5MW scheme to supply all the villages requires longer three phase MV lines and the voltage should be increased to reduce the line losses. The voltage drop, being the main constraint for the conductor size selection, the following configuration was used for MV distribution network voltage drop calculations.

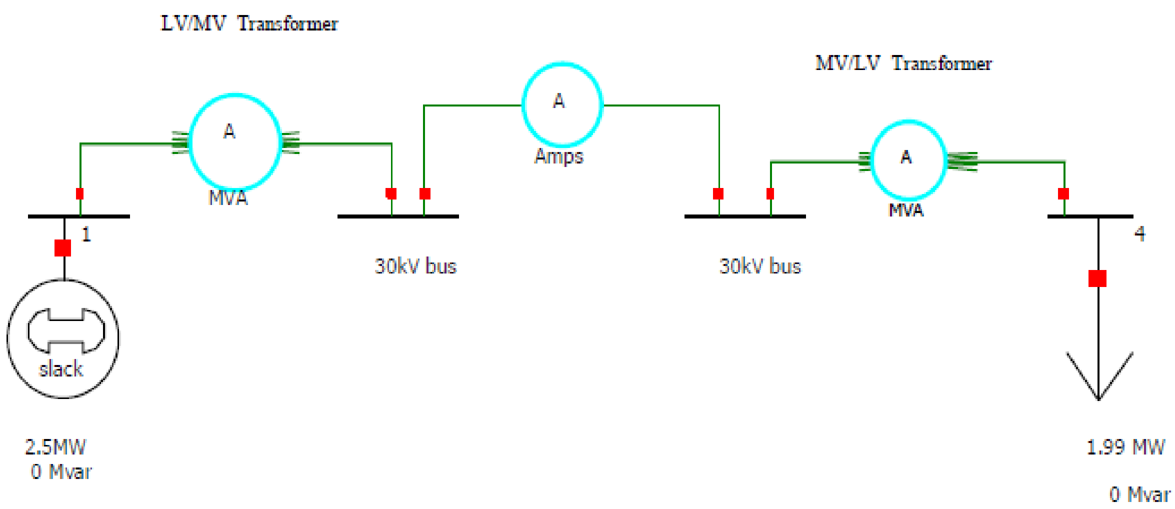


Figure 4-7: Set up for voltage drop calculation in 30kV MV line

The voltage drop results for 70/12 ACSR bare conductor for different line lengths are shown in table 4-14 below:

Table 4-14: MV voltage drops for different 30kV MV line lengths using 70/12 ACSR bare conductor

Line length [km]	Voltage drop [%]
30	2.9
40	3.9
50	4.97
60	6.03
70	7.13
80	8.27

From the results obtained and presented in table 4-14 above, and for the purpose of maintaining the allowable voltage drop limits, two MV feeders, 80km long using 70/12 ACSR bare conductors are found to be required.

4.9 Summary

Chapter 4 has discussed different data required for the cost comparison of hydropower options for rural electrification in Rwanda. The village model was established based on the population densities in rural areas of Rwanda. Depending on the type of supply, mini-hydro scheme size was chosen as 130kW and the single small hydropower plant capacity of 2.5MW was chosen.

The calculation of the voltage drops in LV distribution feeders was done so as to determine the size of conductors appropriate for both LV and MV distribution lines. Herman beta pdf spreadsheets were used for voltage drop calculations in LV feeders whereas Power world simulator was used for MV voltage drops and conductor selection.

The size and number of transformers per village were selected based on the LV single-phase distribution lines and the transformers' position inside the villages served as the basis to calculate the length of MV network required per village.

In case of mini-hydropower schemes, SWER technology was used for MV lines (15kV) and single-phase adopted for LV distribution lines. In case of a centralized power supply produced by a single small hydropower plant, three phase MV lines (30kV) should be used due to high power to be transmitted and long MV distances to be covered by the lines.

The following two chapters (Chapter 5 and Chapter 6) discuss the cost of the two options of supply and deduce the cost of electricity distribution per household. This serves as the basis to compare the two options of hydroelectric power supply in rural areas of Rwanda.

5 COST OF A RURAL ELECTRIFICATION PROJECT IN RWANDA USING MINI HYDROPOWER TECHNOLOGIES

5.1 Introduction

This part of the work is intended to calculate the cost of supplying electricity to rural households in Rwanda by using mini-hydropower schemes. The cost of the village distribution network is calculated and from that, the cost per household is deduced. Taking into consideration the power supply option (mini-hydropower plants), the total cost to electrify 4,976 households grouped in 98 rural villages will also be obtained.

5.2 Components and their costs

The cost of the distribution system includes both the costs of MV and LV lines as well as the cost of transformers. The following are the costs of different components as given in Rwanda electricity master plan [2009]:

MV lines: According to [RECO-RWASCO, 2009], a three phase MV line constructed using 70/12 ACSR conductors on wooden poles is estimated to 15,500USD per km. Assuming the cost of a line to be proportional to the conductor size, the cost of a SWER line constructed using 18.7mm^2 ACSR conductor can be estimated to 1035USD/km. On the other hand, this document shows that 1km of such line using 34mm^2 Aluminium conductors was assigned a cost of 3,036USD. For the purpose of this study, the same cost of **3,036USD** per km of SWER MV line was considered to be a good estimate for an MV SWER line using wooden poles.

MV/LV substations: The cost of substations given below includes all the substations accessories. A 25kVA substation costs 5,850USD and 50kVA substation costs 8,320USD. Using these values, an estimate of around **3,659USD** can be assigned to a 10kVA transformer substation (This is a pole mounted transformer type).

LV lines: The cost obtained here in case of Rwanda is the cost of a three phase LV line because it is the currently most used. For rural electrification, it is clear that three phase LV line is expensive and not needed due to small and dispersed loads to be supplied. As a three phase LV distribution line using 3*50mm^2 Aluminium conductors and 54.6mm^2 neutral wire is estimated to 26,331USD in Rwanda, the cost of a single-phase line using ABC25 conductors was estimated at 50% of this cost and **13,166USD** was used for this study.

5.3 Total cost for 98 villages

Using the data in section 5.2, the calculation of cost per village is as shown in table below.

Table 5-1: Distribution costs per village

Village type & distribution equipments	Unit	Quantity	Unit cost [USD]	Total cost [USD]	Cost per HH [USD]
Large					
MV SWER	km	2.12	3,036	6,436	
LV	km	1.73	13,166	22,751	
Transformer	10kVA	5.00	3,659	18,295	
				47,482	**495**
Medium					
MV SWER	km	2.16	3,036	6,558	
LV	km	1.44	13,166	18,959	
Transformer	10kVA	4.00	3,659	14,636	
				40,153	**535**
Small					
MV SWER	km	1.35	3,036	4,099	
LV	km	1.04	13,166	13,627	
Transformer	10kVA	2.00	3,659	7,318	
				25,043	**677**

From the table 5-1, it is observed that the cost per household goes up as the population density reduces. This explains the high costs encountered in rural electrification projects due to the nature of dispersed population.

The following graph in figure 5-1 shows how the distribution cost varies with the population density.

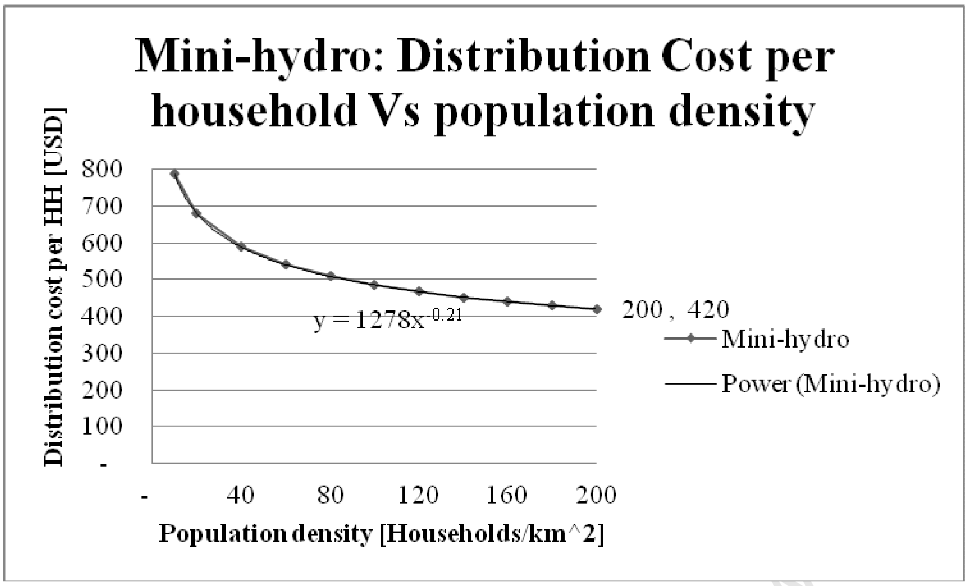


Figure 5-1: Distribution cost per household Vs population density (Case of mini-hydropower plants)

Figure 5-1 shows the impact of the population density on the distribution cost per rural household. As shown by the equation $y = 1278X^{-0.21}$ in figure 5-1, the increase in density results in reduction of the distribution cost. The equation relating the two variables is shown on figure 5-1 and can be used to estimate the approximate distribution cost for a rural household in Rwanda while developing mini-hydropower schemes for electrification of remote rural areas.

As the objective is the electrification of 98 villages with mini-hydropower schemes, the following tables show the total cost of the project as well as the average cost per household.

Table 5-2: Distribution cost for 98 villages

Village type	MV & LV cost per village [USD]	No of villages	Total MV & LV costs [USD]
Large	47,482	10	474,822
Medium	40,153	20	803,056
Small	25,043	68	1,702,952
			2,980,830

Table 5-3: Cost of mini hydro schemes and their MV connections

Mini hydro	**Qty [kW]**	**Number**	**Unit cost [USD/kW]**	**Total cost [USD]**
	130	17	4,000	**8,840,000**
MV connection	Qty [km]	Number	Unit cost [USD/km]	Total cost [USD]
	2	17	3,036	**103,224**

Table 5-4: Total cost and average cost per household

Total Cost per 98 villages [USD]	**11,924,054**
Average cost per household [USD]	**2,396**

5.4 Summary

As calculated in this section, the cost of the distribution systems in rural areas depends on the nature of the population density. As shown by the cost variation in section 5.3, for a large village, the cost per household is slightly low as compared to medium and small villages where the population densities are low. The general average cost of distribution per household in rural areas of Rwanda using mini-hydro schemes can be found to be **569USD**.

We should not forget the additional MV lines to be used while connecting a mini-hydropower plant to the first village in a series of villages to be supplied by mini-hydro schemes. This MV line was assumed to be 2km for each mini-hydropower station. Summing up all the cost and finding the total cost of the project results in the average of **2,396USD** per household. This cost includes both the distribution system and the plant construction.

6 COST OF A RURAL ELECTRIFICATION PROJECT IN RWANDA USING SMALL HYDROPOWER TECHNOLOGIES

6.1 Introduction

In this case, a single small hydropower plant of 2.5MW is used to supply electricity to 98 rural villages as previously done. As the position of MV/LV transformer substations inside the villages is the same as in the previous case, the following parameters are kept constant:

- The number of villages
- Total MV line length per village
- Total LV line parameters and length
- The size, cost and number of MV/LV substations

The following parameters will change due to a centralized type of electrical power supply:

- The voltage level of the MV line from the small hydropower plant
- The cost of the new MV line/km
- The construction cost/kW of the small hydropower plant

Taking into consideration all these parameters, the cost of electrification is obtained.

6.2 Components and their costs

Due to increase in power to be transmitted; the total MV distance to be covered and the centralized power supply system, the MV line voltage level was increased to 30kV and therefore the cost/km of MV line will change. According to table 4-14, the voltage drop calculations have shown that the maximum distance to be covered by a 30kV using 70/12 ACSR conductor as currently used for the same type of MV lines in Rwanda is 80km.

As the total MV required for the connection of 98 villages is 156.2km, two branches of MV feeders are required to satisfy the requirement. To account for this, the following data are considered for the cost calculation:

- The total length of 30kV MV line required to supply 98 villages is 156.2km
- The cost of a 30kV MV line constructed using wooden poles is 15,500USD/km as discussed in section 5.2.
- The cost per kW produced by a small hydropower plant was taken as 3,500USD/kW.

6.3 Calculation of the total cost for 98 villages

Using data as set in section 6.1 and 6.2, the cost per village in case of a small hydropower plant supplying all 98 villages can be calculated as shown in the following table.

Table 6-1: Small hydropower option: Distribution cost per village

Village type	**Unit**	**Quantity [km]**	**Unit cost [USD]**	**Total cost [USD]**	**Cost per HH [USD]**
Large					
MV SWER	km	2.12	15,500	32,860	
LV	km	1.73	13,166	22,751	
Transformer	10kVA	5.00	3,659	18,295	
				73,906	**770**
Medium					
MV SWER	km	2.16	15,500	33,480	
LV	km	1.44	13,166	18,959	
Transformer	10kVA	4.00	3,659	14,636	
				67,075	**894**
Small					
MV SWER	km	1.35	15,500	20,925	
LV	km	1.04	13,166	13,627	
Transformer	10kVA	2.00	3,659	7,318	
				41,870	**1,132**

The table shows the cost per village and the average cost per household. It is clear that the cost per household again increases in regions with low population densities. Averaging the cost per household in a rural area of Rwanda, **853USD** would be the approximate cost of distribution per household using a small hydro scheme.

In order to find the total cost, the construction cost of the small hydropower plant should be included and the following results are obtained as shown in figure 6-1 which shows how the distribution cost per household reduces with the increased population density.

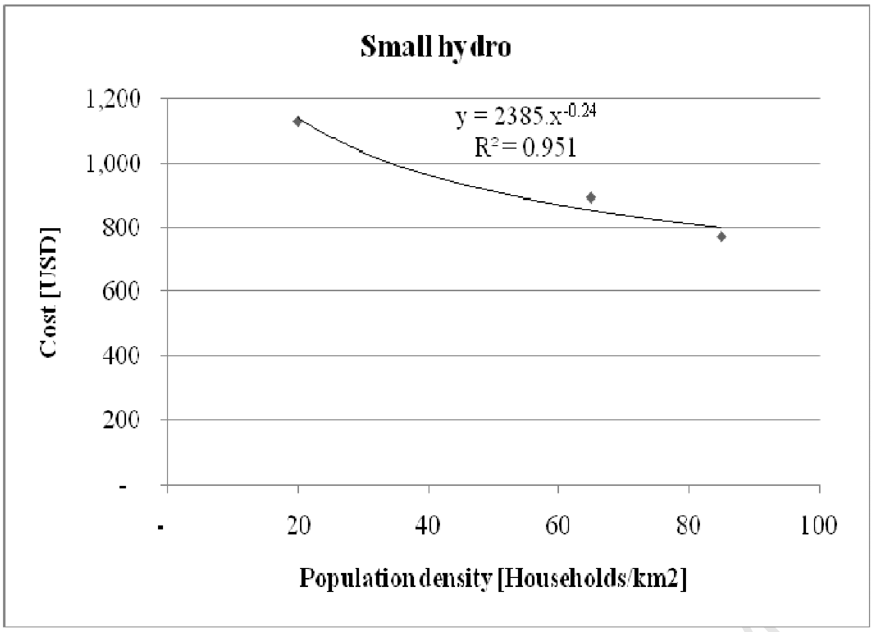


Figure 6-1: Distribution cost per household Vs population density (Small hydro)

Figure 6-1 shows the relationship between the distribution cost per household and the population density in case of a single small hydropower plant developed to interconnect 98 rural villages in Rwanda as used in this analysis. The equation $y = 2385x^{-0.24}$ shows the relationship between the cost and the population density. It is clear that for low population densities, the distribution cost per household is very high when a centralized power supply is used. But for high density areas, this cost becomes relatively very small.

Table 6-2: Total cost for 98 villages

Village type	MV & LV cost [USD]	No of villages	Total MV & LV costs [USD]
Large	73,906	10	739,058
Medium	67,075	20	1,341,501
Small	41,870	68	2,847,147
			4,927,706

Table 6-3: Small hydro cost

Small hydro	**Qty [kW]**	**Number**	**Unit cost [USD/kW]**	**Total cost [USD]**
	2,500	1	3,500	**8,750,000**
MV connection	**Qty [km]**	**Number**	**Unit cost [USD/km]**	**Total cost [USD]**
	2	1	15,500	**31,000**

Table 6-4: Total cost and cost per household

Total cost per 98 Villages [USD]	**13,708,706**
Average cost per household [USD]	**2,742**

Table 6-1 to 6-4 show the costs for different components of rural households' electrification using a single small hydropower plant in Rwanda. It can be observed that the cost per household in this option becomes higher than the costs shown in chapter 5. This is due to the increase in cost of MV lines due to change in voltage level and technology.

6.4 Summary

The intention of chapter 6 was to calculate the cost of a rural electrification project in Rwanda, using a single small size (2.5MW) hydropower plant to electrify 98 villages with a total number of 4,976 households. The results show that the distribution cost per household varies between 770USD, 894USD and 1,132USD for Large, medium and small villages.

It is clear that the cost is high in case of small villages. This explains the high costs of distribution systems in rural areas with low population densities. The average cost per household, including the small hydropower plant construction is found to be 2,742USD.

7 COST OF A RURAL ELECTRIFICATION USING A 10MW HYDROPOWER PLANT

7.1 Introduction

In this case, a 10MW hydropower plant is used to supply electricity to rural villages as previously done. As the power increases, the model is extended and the number of villages increases to 98 village *4=392 villages. The position of MV/LV transformer substations inside the villages remains the same. The following parameters are kept constant:

- Total MV line length per village
- Total LV line parameters and length
- The size, cost and number of MV/LV substations

The following parameters will change due to a centralized type of electrical power supply:

- The number of villages
- The cost of the main MV line/km
- The construction cost/kW of the hydropower plant

The consideration of these parameters helps us to calculate the cost of electrification using a large hydropower plant.

7.2 Components and their costs

Due to increase in power to be transmitted; there is a need of the backbone MV line from which secondary MV distribution lines for the supply of different villages are connected. This line is characterized by large section conductors and therefore increasing its cost. The following data are considered for the cost calculation:

- As a 2.5MW plant was intended to supply 98 rural villages, the increase to 10MW option causes the model to be extended. For this reason, the total length of 30kV MV line required to supply 392 villages is 624.8km
- The cost of a 30kV main MV line is 70,000USD/km.
- The cost per kW produced by a medium/large hydropower plant was taken as 3,000USD/kW.

7.3 Calculation of the total cost for 392 villages

Using data as set in section 7.1 and 7.2, the cost per village in case of a 10MW hydropower plant can be calculated as shown in the table 7-1. The choice of 392 villages is due to the increase of the supply option from 2.5MW to 10MW. Therefore, the number of villages also increased from 98 villages to 392 villages.

Table 7-1: 10MW hydropower option: Distribution cost per village

Village type	**Unit**	**Quantity [km]**	**Unit cost [USD]**	**Total cost [USD]**	**Cost per HH [USD]**
Large					
Main MV	km	0.14	70,000	9,800	
Village MV	km	2.12	15,500	32,860	
LV	km	1.73	13,166	22,751	
Transformer	10kVA	5.00	3,659	18,295	
				83,706	**872**
Medium					
Main MV	km	0.11	70,000	7,700	
Village MV	km	2.16	15,500	33,480	
LV	km	1.44	13,166	18,959	
Transformer	10kVA	4.00	3,659	14,636	
				74,775	**997**
Small					
Main MV	km	0.05	70,000	3,500	
Village MV	km	1.35	15,500	20,925	
LV	km	1.04	13,166	13,627	

Transformer	10kVA	2.00	3,659	7,318	
				45,370	**1,226**

The table shows the cost per village and the average cost per household. The cost per household again increases in regions where population densities are low. Averaging the cost per household in a rural area of Rwanda, **1032USD** would be the approximate cost of distribution per household using a medium (10MW) hydro scheme.

The distribution cost for different population densities is shown in figure 7-1.

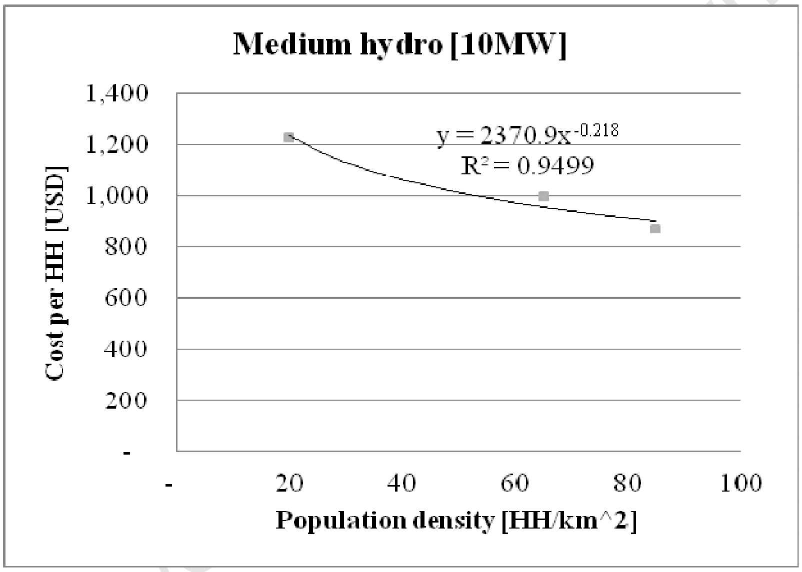


Figure 7-1: Distribution cost per household Vs population density (Medium hydro)

Figure 7-1 shows the relationship between the distribution cost per household and the population density in case of a medium (10MW) hydropower plant. It is clear that for low population densities, the distribution cost per household is very high when a centralized power supply is used whereas for high density areas, this cost reduces.

Table 7-2: Total cost for 392 villages

Village type	MV & LV cost [USD]	No of villages	Total MV & LV costs [USD]
Large	83,706	40	3,348,234
Medium	74,775	80	5,982,003
Small	**45,370**	**272**	**12,340,588**
			21,670,825

Table 7-3: Medium hydro cost

Small hydro	Qty [kW]	Number	Unit cost [USD/kW]	Total cost [USD]
	10,000	1	3,000	**30,000,000**
Main MV	**Qty [km]**	**Number**	**Unit cost [USD/km]**	**Total cost [USD]**
	30	-	70,000	**2,100,000**

Table 7-4: Total cost and cost per household

Total cost per 392 Villages	**53,770,825**
Average cost per household	**2,702**

Table 7-1 to 7-4 show the costs for different components of rural households' electrification using a 10MW hydropower plant. It can be observed that the cost per household in this option becomes lower than the costs shown in chapter 6. This is due to increased number of connections and the reduction in cost per kW of the plant construction.

7.4 Summary

In this chapter, a medium (10MW) hydropower plant was considered for electrification of rural households in 392 villages. The results show that the distribution costs per household are 872USD, 997USD and 1,226USD for Large, medium and small villages.

It is clear that the cost is high in areas with low population densities. The average cost per household, including the plant construction is found to be 2,702USD. The costs obtained in this chapter are to be compared with the costs found in chapter 5 and 6 and the comparison of the three options is done in chapter 8.

8 DISCUSSION OF THE RESULTS

The costs of rural electrification in Rwanda using mini, small and medium hydropower technologies were calculated in chapters 5, 6 and 7. According to the results found in chapter 5 where mini-hydropower plants are used to electrify rural villages, it was realized that the population density is a major concern on the total cost of a rural electrification project.

The villages with low population densities present a distribution cost per household which is relatively higher than the villages with high densities. This is the same for all the options. The average figures per household show that for rural areas where the population densities are low and there is a hydropower potential, setting up many mini-hydropower projects for electrification is the cost effective option as compared to the development of a single small or medium hydropower plant to interconnect all the villages.

Figure 8-1 is used to compare the three options based on the way the cost per household varies with the population density.

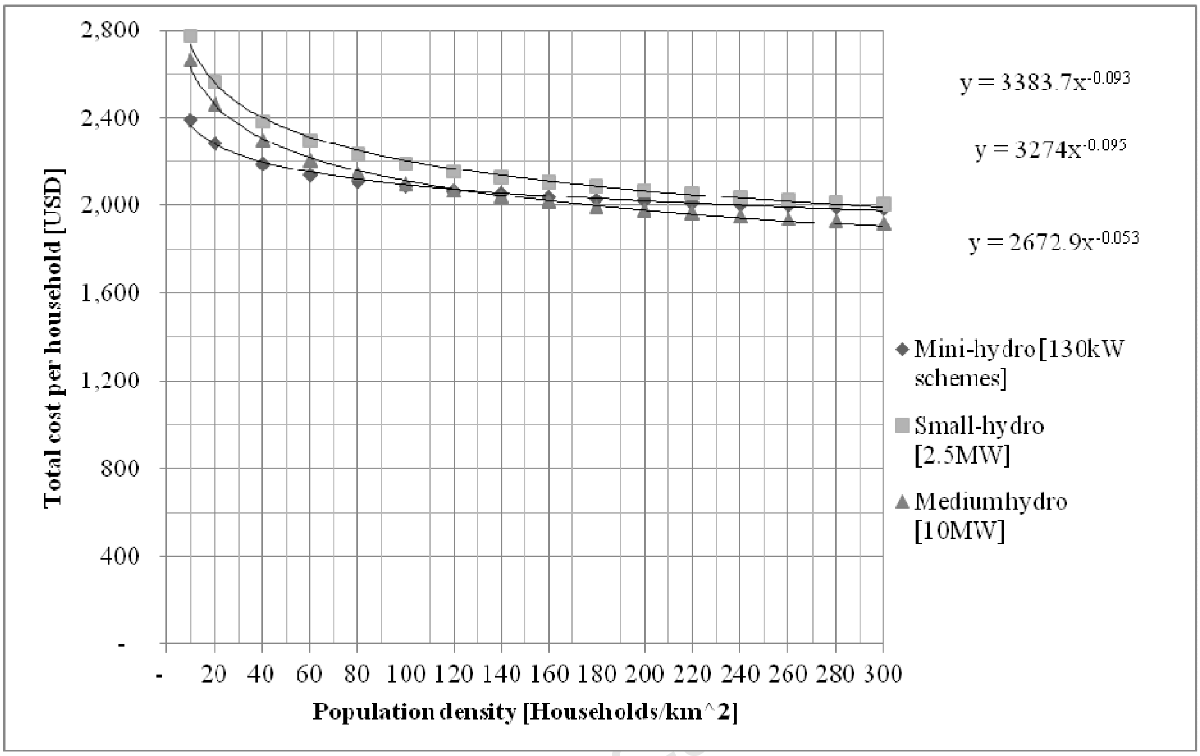


Figure 8-1: Total cost per household Vs population density (Case of mini, small and medium hydropower plants)

Figure 8-1 shows the variation of the total cost per household with respect to population density. The increase in cost per household in low density areas in case of a small hydropower plant is remarkably due to change in MV distribution line technology. The three phase MV line was used here because of the amount of power to be transmitted and the total distance to be covered in order to interconnect all the villages.

The three curves shown in figure 8-1 help us to estimate the average total electrification cost per rural household in Rwanda with respect to population density and the type of hydropower technology used.

The effect of economies of scale should not be neglected because it affects the total cost because the cost per kW reduces with the plant size.

From Figure 8-1 and equating the two equations $3274X^{-0.095} = 2672.9X^{-0.053}$, *the value of X=125.17 shows that for population densities below 125 households/km*^{2}*, the development of mini-hydropower schemes results in low total cost per household whereas for densities* *above 125 households/km^2, the development of medium or large hydropower plant is a low cost option. The use of small hydropower plants for electrification should not be considered because it is not a viable option and always presents a high cost.*

This explains the efficiency of using small scale generation and decentralized distribution systems in low density rural areas and the reason why high density areas such as urban centers and big cities are supplied using large scale hydropower plant projects.

9 CONCLUSION AND RECOMMENDATIONS

9.1 To the Government of Rwanda

Rural electrification in Rwanda should be carried out most appropriately using mini-hydropower instead of small centralized hydropower plants. This can be justified by the findings obtained in chapter 5, 6 and 7 where the three approaches were evaluated and the distribution costs per household deduced.

It is clear that the use of a large number of mini-hydropower plants for electrification of remote rural areas of Rwanda is the cheapest option for a range of population densities. This is due to the reduction in cost of MV distribution lines because small size conductors and short MV lines can be used for electricity distribution to rural households.

The use of SWER for MV distribution lines has considerably contributed in cost reduction of the distribution system because the technology allows the use of one conductor for MV line and the size of this conductor is small due to the amount of power produced by a mini-hydropower plant considered here as 130kW.

It should be therefore recommended that the rural electrification in Rwanda would be planned considering the potential in hydropower resources available in close proximity of the villages to be electrified. The priority should be given to mini-hydropower plants because they can supply the typical loads of rural households at a low cost.

The development of small or large hydropower plants in rural areas where the population densities are low presents the disadvantage in terms of cost. These large schemes are very expensive in areas where populations are sparse.

The increase of the distribution cost observed in small and medium hydropower projects is due to the centralized nature of supply and the capacity of the plant itself which imposes the use of expensive transmission lines. As shown in figure 8-1, a medium hydropower scheme should be efficient where the population density is high (above 125 households/km^2).

9.2 People interested in hydropower development for rural electrification

Before setting up a hydropower scheme for electrification of remote area, the population density and its dispersion should be first taken into account for the network design. It should be unrealistic to use the countrywide average population density for LV network design in rural electrification because this can result in overdesign of the network and increases the cost of the project.

A proper selection of parameters such as the power consumption per household and the way households are arranged in the region is an important factor that helps to determine the technology to be used and results in low cost and reliable rural electrification.

The distribution network should be designed using the accurate parameters and design methods. The voltage drop calculation methods using Herman beta pdf spreadsheets provide reliable results for the selection of LV conductors to be used. This proper selection of LV feeder conductor helps in cost minimization and results in increased reliability of the distribution network.

MV and LV distribution lines technology should be carefully selected based on the amount and the type of loads to be supplied. The cost of MV distribution lines is of great importance for rural electrification because it plays a big role in the overall cost of the project. Therefore, a proper selection of technologies should help into a cost effective and reliable rural distribution network.

The number and size of MV/LV distribution transformers should not be neglected because the use of bigger size transformers in rural areas results in expensive LV distribution networks due to increase in LV conductor size required for the distribution feeders.

Due to the nature of dispersed population structure of rural areas in Rwanda, the cost reduction was done by using small size transformers of 10kVA. It was found that the use of small size transformers resulted in small sections of LV conductors and therefore helps in cost reduction of LV distribution lines.

Increasing the number of transformers results in increasing the length of MV line but the increased cost is relatively small as compared to the use of large size transformers which cause a considerable increase in cost of the whole LV distribution network.

9.3 Validity of the hypothesis and answers to the research questions

The hypothesis to be tested by the research was formulated as follows:

"Rural electrification in Rwanda could be carried out most appropriately using mini hydropower plants with short distribution lines instead of using small hydropower schemes with long distribution lines." As shown by the results interpreted in Chapter 8 of this dissertation, the hypothesis was tested and proved to be valid. The cost of access to electricity per household in three cases of small, mini and medium hydropower schemes shows that the use of small scales results in low cost per household and this proves our hypothesis.

By proving the validity of the hypothesis, various research questions were answered:

1) What is the status of electrification in Sub-Saharan Africa and what is the situation in Rwanda?

This question was answered in chapter 1 where figure 1-3 shows the status of electrification in sub-saharan African region and the situation is in Rwanda was presented in chapter 2 where the general informations about electrification in Rwanda were given.

2) What are the different types of hydroelectric power plants and how can these be applied to rural electrification?

The definition of hydropower and its different types were addressed in chapter 2. According to the findings from other researches conducted, the application of hydroelectric power to rural electrification in Rwanda was deduced.

3) What are the different electricity distribution technologies and which one is cost effective as far as rural electrification is concerned?

Chapter 3 has enumerated different types of electricity distribution technologies from 3-phase distribution to Single Wire Earth return technologies. In each case, the cost effectiveness depends on the type of population targeted. It was found that the nature of the load in rural areas of most countries makes single phase distribution technologies the most cost effective.

4) How can the rural electrification model be done?

Modeling the rural electrification requires information about the load parameters. In chapter 2, depending on the types of rural household's load assumed in table 2-12 and the design minimizing the distribution cost; the household model was established and applied in this research.

5) What is the impact of the population density on electricity distribution system infrastructures?

As shown by the results from the analyses done in chapter 5, 6 and 7, there is a big impact of the population density on the distribution system infrastructure. This impact occurs in both the design and cost involved. The lesser the population density, the lesser the load density and therefore the electricity infrastructures are also different. For the case of electrification, the high population density areas are characterised by 3-phase distribution technologies whereas low population density areas are supplied with single or dual phase technologies.

6) What is the approximate cost of supplying electricity to a typical rural household in Rwanda using mini, small and medium hydropower schemes?

The approximate cost of supplying electricity to a typical rural household in Rwanda using the three hydropower schemes was calculated for different types of villages. The cost was found to be 495USD, 535USD and 677USD per household in large, medium and small villages respectively.

7) Which hydropower option is the least cost for rural electrification in Rwanda?

For the purpose of the least cost option, small hydropower plants were found to be the best option as far as a rural household in Rwanda is concerned.

9.4 Future work

Sections 9.1 and 9.2 contain the conclusions and recommendations to both the Government of Rwanda and people interested in hydropower development for rural electrification in general. From the findings of this research, it is clear that the cost of a rural electrification is firmly related to the population density. Different relationships were derived during this study and for different cases.

- The future work would go in deep and establish a clear relationship between other electricity generation technology, the population density and the cost of electrification. This will facilitate the planners of the rural electrification to easily decide the priorities in both generation and distribution technologies to apply when a rural electrification project is envisaged. Also the future work should emphasize on technical losses in order to optimize the conductor sizes and MV technology used.

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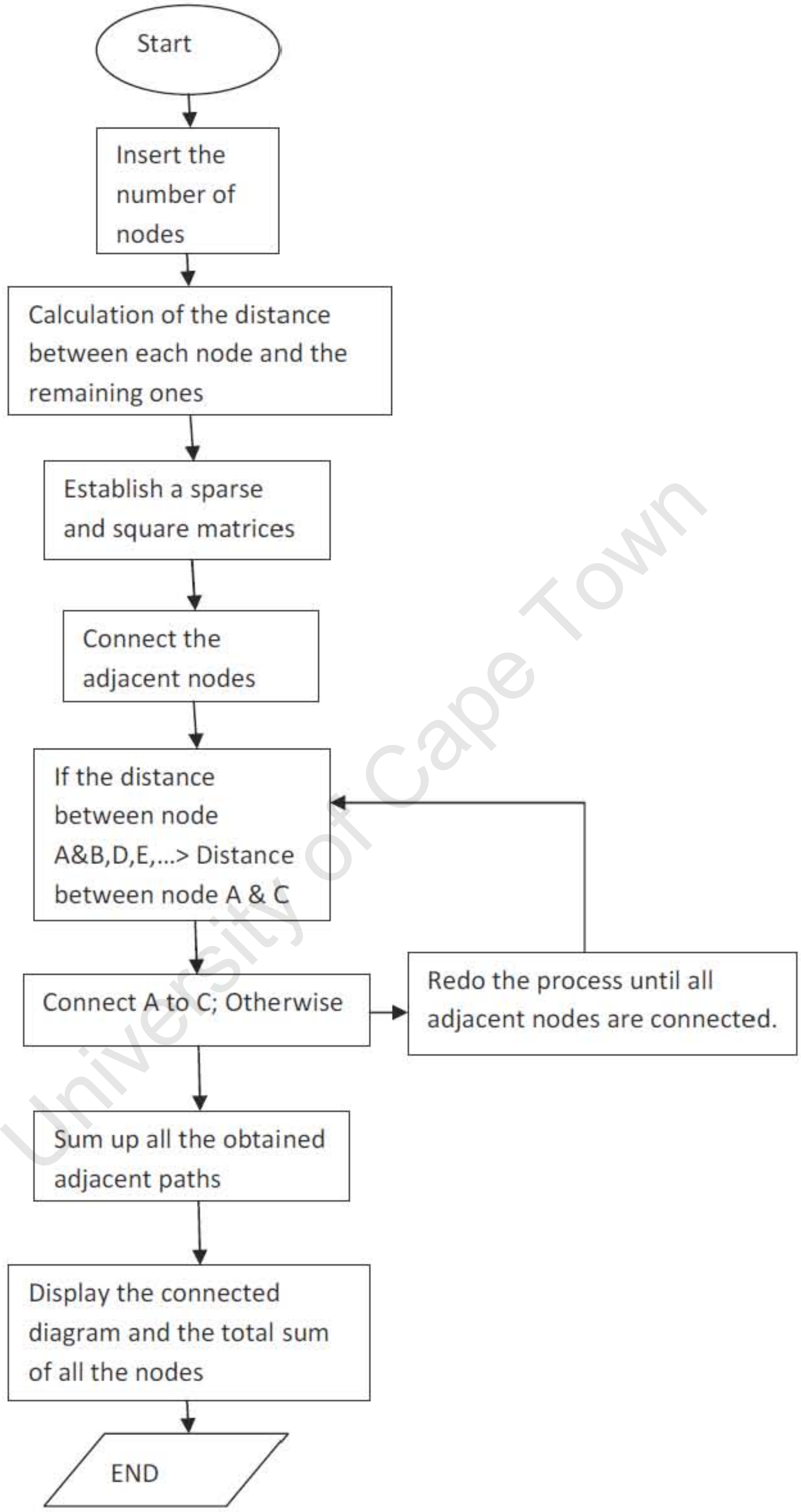
11 APPENDICES

APPENDIX-A: Minimum spanning tree algorithm and its flow chart for a dispersed population LV network length calculation

```
n=10;
XY=randint(n,2,[0,100]),
A=pdist(XY);
B=squareform(A);
DG=sparse(B);
UG=tril(DG);
view(biograph(UG,[],'ShowArrows','off','ShowWeights','on'))
[ST,pred]=graphminspantree(UG);
view(biograph(ST,[],'ShowArrows','off','ShowWeights','on'))
[n,n]=size(B);
B,n,
if norm(B-B','fro') ~= 0 ,
  disp(' Error:  Adjacency matrix must be symmetric ')
  return,
end;
intree = [1];  number_in_tree = 1;  number_of_edges = 0;
notintree = [2:n];  number_notin_tree = n-1;
in = intree(1:number_in_tree);
out = notintree(1:number_notin_tree);
while number_in_tree < n,
  mincost = Inf;
```

```
  for i=1:number_in_tree,
    for j=1:number_notin_tree,
      ii = intree(i);  jj = notintree(j);
      if B(ii,jj) < mincost;
        mincost = B(ii,jj); jsave = j; iisave = ii; jjsave = jj;
      end;
    end;
  end;
  number_of_edges = number_of_edges + 1;
  mst(number_of_edges,1) = iisave;
  mst(number_of_edges,2) = jjsave;
  costs(number_of_edges,1) = mincost;
  number_in_tree = number_in_tree + 1;
  intree = [intree; jjsave];
  for j=jsave+1:number_notin_tree,
    notintree(j-1) = notintree(j);
  end;
  number_notin_tree = number_notin_tree - 1;
  in = intree(1:number_in_tree);
  out = notintree(1:number_notin_tree);
end;
disp(' Edges in minimum spanning tree and their costs: ')
[mst  costs]
cost = sum(costs)
```

APPENDIX-A (CNTD): Flow chart of the algorithm in APPENDIX-A



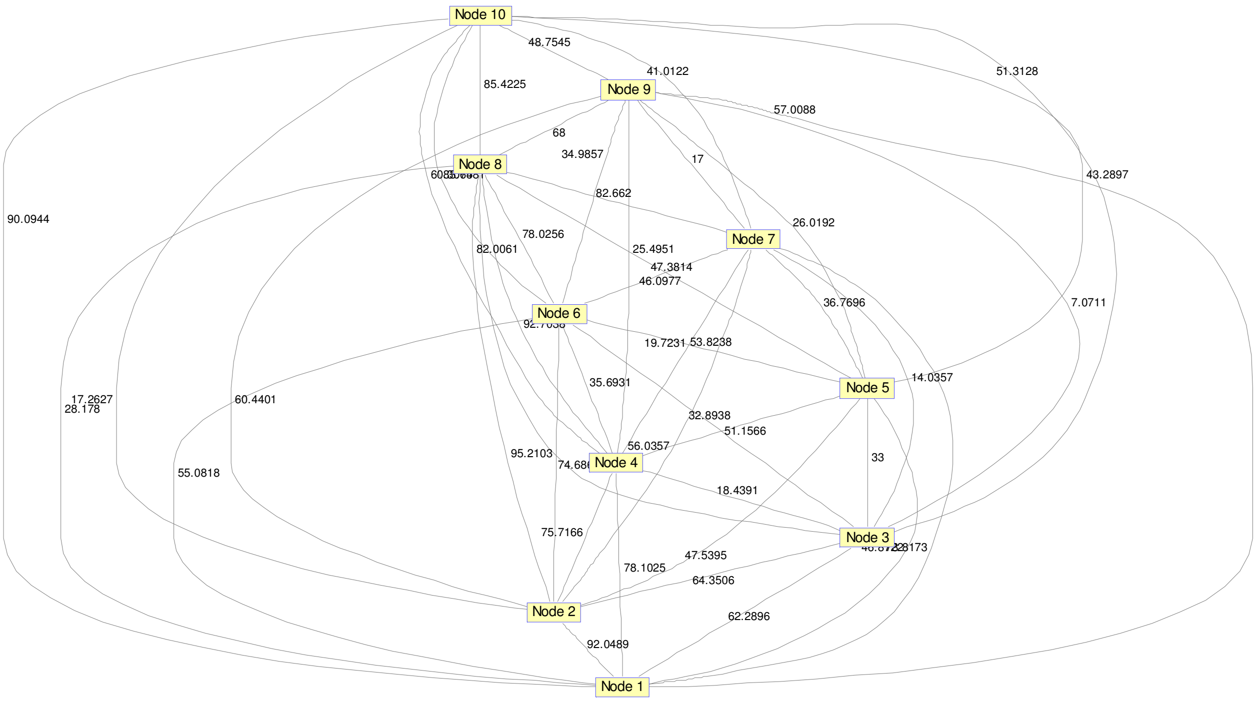
APPENDIX-B: Random coordinates and Minimum inter-households distances

B-1: 10 households

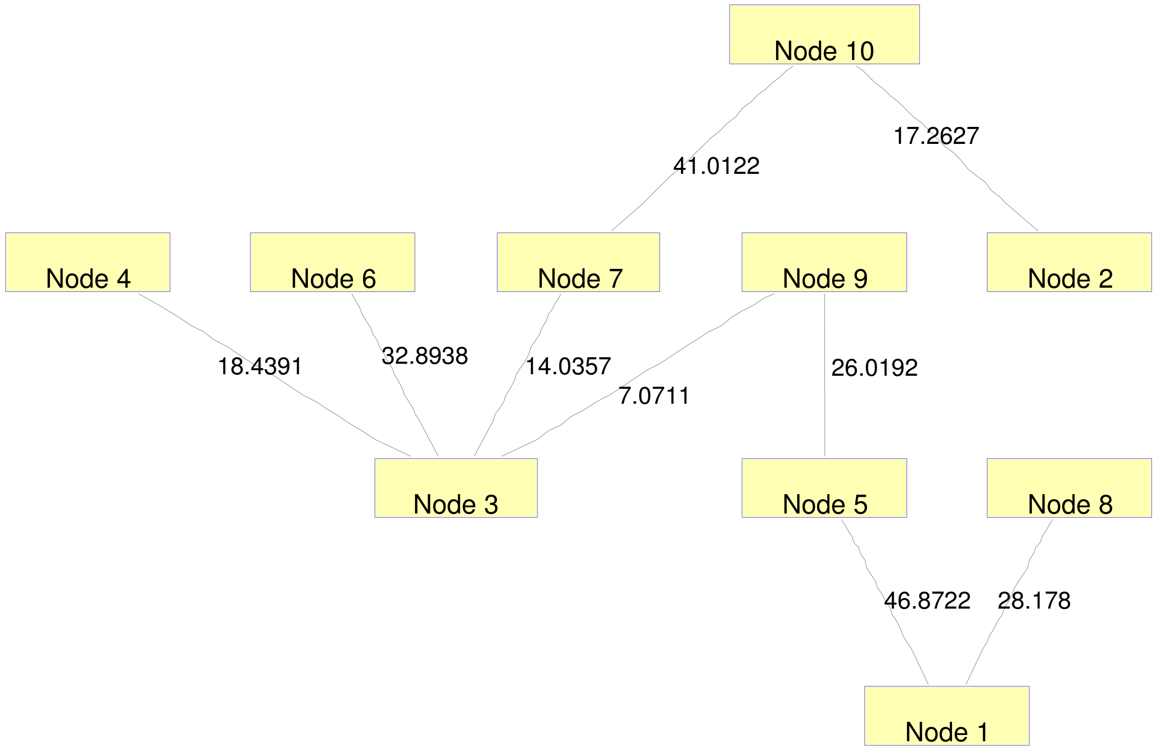
10*10 Distance matrix

0	92.0489	62.2896	78.1025	46.8722	55.0818	73.8173	28.1780	57.0088	90.0944
92.0489	0	64.3506	75.7166	47.5395	95.2103	56.0357	82.0061	60.4401	17.2627
62.2896	64.3506	0	18.4391	33.0000	32.8938	14.0357	74.6860	7.0711	51.3128
78.1025	75.7166	18.4391	0	51.1566	35.6931	19.7231	92.7038	25.4951	60.3075
46.8722	47.5395	33.0000	51.1566	0	53.8238	36.7696	47.3814	26.0192	43.2897
55.0818	95.2103	32.8938	35.6931	53.8238	0	46.0977	78.0256	34.9857	83.6481
73.8173	56.0357	14.0357	19.7231	36.7696	46.0977	0	82.6620	17.0000	41.0122
28.1780	82.0061	74.6860	92.7038	47.3814	78.0256	82.6620	0	68.0000	85.4225
57.0088	60.4401	7.0711	25.4951	26.0192	34.9857	17.0000	68.0000	0	48.7545
90.0944	17.2627	51.3128	60.3075	43.2897	83.6481	41.0122	85.4225	48.7545	0

Possible nodes interconnections:

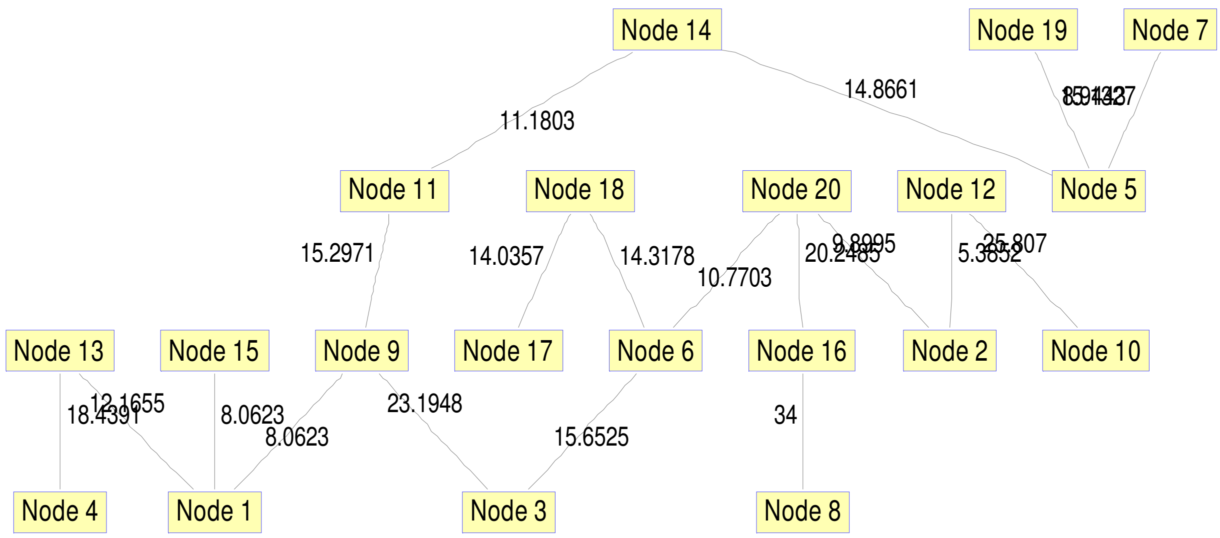


Minimum distance between nodes:



B-2: 20 households

Distance between nodes



APPENDIX-C: Example of Herman beta pdf voltage drop calculation sheets

The data in C-1 o C-3 are the inputs and the outputs are displayed in C-4

C-1: Input parameters

CABLES	°C
t1	20
t2	***40***

Nom Voltage	***230.00***

% Volt Limit	***10***

Vs	*230*
D risk%	*10.00*

C-2: Conductor types

Code	R/km@t2	R/km@t1	T	k	Description
ABC25	1.297	*1.20*	*228*	*0.5*	*ABC 25 mm² Al French std*
ABC35	0.938	*0.87*	*228*	*0.7*	*ABC 35 mm² Al French std*
ABC50	0.693	*0.64*	*228*	*1*	*ABC 50 mm² Al French std*
ABC70	0.479	*0.44*	*228*	*1.4*	*ABC 70 mm² Al French std*
ABC95	0.346	*0.32*	*228*	*1.9*	*ABC 95 mm² Al French std*
A10	2.035	*1.89*	*241*	*1*	*AIRDAC 10mm² Cu*
35mmCu	0.564	*0.52*	*241*	*1*	*35 mm Copper*
50mmCu	0.417	*0.39*	*241*	*1*	*50 mm Copper*
70mmCu	0.289	*0.27*	*241*	*1*	*70 mm Copper*
95mmCu	0.208	*0.19*	*241*	*1*	*95 mm Copper*

C-3: Consumer phase assignment

	No Consumers		Load Parameters			Conductor	
Node	Red	Blue	Alpha	Beta	Cb	Length	Cable
	ma	mb			[A]	[m]	Code
1	*1*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
2	*2*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
3	*3*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
4	*3*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
5	*2*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
6	*1*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
7	*1*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
8	*2*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
9	*3*	*2*	***0.355***	***3.536***	***20.00***	*72*	*ABC35*
10			***0.355***	***3.536***	***20.00***	*72*	*ABC35*

C-4: Output from Herman beta pdf voltage drops

Results	Red	Blue	Unit
%-tile Vcon	**208.37**	**209.09**	V
%Volt drop	**9.40**	**9.09**	%V
%-tile Isum	**47.60**	**47.60**	A
Mean Isum	**32.85**	**32.85**	A
Stdev Isum	**11.05**	**11.05**	A

APPENDIX D: MAP OF RWANDA AND ITS LOCATION IN AFRICA

Source: Institut National de la Statistique du Rwanda, 2005.

Source: UNCTAD, based on map of Africa by United Nations Cartographic Section, 2004.